BUILDINGS AND WIND

A Software-Based Design Methodology

by

Stephanie Fleming

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AUTHOR'S DECLARATION

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

ABSTRACT

There is a reciprocal relationship between wind and buildings, as they each affect the other. Building form affects wind by altering its speed and flow patterns, and can be used to create desirable wind conditions around the building. Wind, in turn, exerts load on the building, which can be reduced with aerodynamic forms and resisted with structural systems. This establishes a relationship between wind conditions, the building form that creates these wind conditions, and the structure that stabilizes the form against these wind conditions.

This relationship is investigated through the development of a design methodology that allows architects to consider, in the early design stages, how wind and buildings affect each other. The thesis does not serve to propose a building; rather, it will use a building as a means for developing this method. The method consists of a pairing of computational fluid dynamics (CFD) software and finite element analysis (FEA) software. While this pairing has not been widely explored within the context of architectural design, the combined use of these software programs allows architects to integrate wind engineering considerations into their current architectural practices, without having to acquire extensive engineering knowledge. Software also provides architects with a means of quickly testing multiple design iterations in relation to these engineering considerations, because the software can perform engineering calculations or simulations much faster than if the architect were to learn and perform these calculations themselves.

For each building design iteration, CFD software is used to simulate the speeds and patterns of wind flow around the initial building form design. This tests the appropriateness of the wind conditions for the exterior programs that must be accommodated around the building. The speed with which these results are provided allows the architect to refine and re-test many iterations of their design until the building form creates the desired wind conditions. The CFD software is then used to evaluate the aerodynamics of the building form by providing information about the wind pressure that is exerted on each building face. The architect can change the building form to reduce the wind pressure acting on it, and then re-test the form with the CFD software to ensure that improved aerodynamics have been achieved without compromising the surrounding wind conditions. Then, the wind pressure information that is provided by the CFD software is input into the FEA software to predict how the building will react to combined wind and gravity loading. This information informs the schematic design of the building's structural system, which is developed through another iterative process using the FEA software.

The production of accurate wind and structural data is not the goal of this thesis, since accurate results are not currently available due to software limitations. Instead, this thesis seeks to develop a design method that will increase in accuracy as CFD and FEA software programs continue to be improved. In the future, CFD and FEA software programmers could potentially draw from this method to create programs that can be used together, to allow architects to consider wind as a generator of architectural form within a streamlined, software-based workflow.

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1 “Wind is moving air. The air has a particular mass (density or weight) and moves in a particular direction . . . When the moving fluid air encounters a stationary object, there are several effects that combine to exert a force on the object.”

James Ambrose and Dimitry Vergun, *Simplified Building Design for Wind and Earthquake Forces*[1]

2 “What a character the wind is . . . An all powerful ruler, sometimes terrible, sometimes charitable . . . he who can be used, avoided, or fled from, but who can never be tamed.”

Guy de Maupassant, *Sur l'eau*[2]

WORKFLOW

INTEGRATION OF ARCHITECTURAL AND ENGINEERING PROCESSES

Within current architectural practice there is a separation between architectural and engineering design processes, as engineering analysis is not often integrated into the early architectural design phases. Instead, it is performed by an engineer after the initial building design has already been developed by the architect, at a point when it is often difficult, costly, and time-consuming to change the design to accommodate the engineering requirements. This separation is widely acknowledged in the fields of both architecture and engineering, and members of both professions have worked on developing methods of integrating the two design processes. This thesis explores one such method of integration, through the creation of a design methodology that architects can use to consider wind loading and effects as design informants that are integrated into the initial architectural design phases. This allows both structural and wind engineering considerations to be included in the architectural design process.

In antiquity, the architect was the “master builder”[1] who understood and was able to execute both building design and construction.[2] However, when the Industrial Revolution spurred the rapid creation of many new building materials and technologies, it became difficult for a single person to master them all.[3] This fostered the creation of the structural engineering profession.[4] Structural engineers became experts in building construction technologies,[5] while architects specialized in the spatial and aesthetic design of buildings.[6] This has resulted in a divergence between the roles and priorities of the architect and the structural engineer.

One method of integrating structural engineering considerations into the architectural design process is for the architect to develop a **qualitative structural understanding**. There are several ways in which a structural form can be generated without scientific structural analysis, including observation of natural forms, structural intuition,

Qualitative structural understanding
The ability to know how a structure behaves without referring to measurements or calculations.

Fig. 1.1. Trees are naturally structurally efficient.

Fig. 1.2. This rock formation maintains a structurally efficient form.

Structural intuition

The ability to immediately understand how an object or material will act under load, without necessarily knowing why.

Fig. 1.3. Stacking blocks can develop structural intuition.

Fig. 1.4. Feeling a diving board's deflection can develop structural intuition.

and physical models. These tools can help architects develop a qualitative structural understanding, which is necessary for them to consider space and structure simultaneously in the design process.

For example, natural forms (Fig. 1.1, Fig. 1.2) are made structurally efficient to withstand the environment, and have always provided humans with forms that we can mimic and know that they will be structurally stable.[7] As we grow up, **structural intuition** is subconsciously developed through activities such as stacking blocks as a child (Fig. 1.3) or feeling a diving board deflect under our weight (Fig. 1.4), which allow everyone to develop an idea of how structural forms work without necessarily knowing why they work.[8] Small-scale physical models (Fig. 1.5) can also be used to demonstrate a form's structural behaviour.[9] Because these methods of structural form generation do not require scientific structural analysis, they allow architects to design structures with a qualitative idea of whether or not they will work. This understanding needs to be developed by architects to be able to carry out a design method that integrates architectural and engineering considerations.

This qualitative understanding of engineering principles may also be developed through the use of software, such as **finite element analysis (FEA) software** (Fig. 1.6). Gary Black and Stephen Duff, who are architecture and engineering professors at the University of California, Berkeley, developed a structural education model for architecture students that emphasizes the importance of learning **structural design**, rather than just **structural analysis**, and facilitates this through the use of finite element analysis software as a learning tool.[10] They taught this model with great success for six years at the University of California, Berkeley.[11] This educational model was developed because many structures courses for architecture students, both at the time and today, only teach a condensed version of the structural analysis courses for engineering students, which do not cover structural design.[12] As a result, architectural graduates are often unable to apply structural principles during the architectural design process.[13] To combat this, the use of FEA software as a learning tool allows users of this educational model to quickly see and understand how forces act within the structures they design and input into the program without their having to learn engineering calculations.[14] The quick feedback that is provided allows students to develop a qualitative structural understanding, and teaches them how to design while constantly considering structural feasibility.[15] As they build up this qualitative structural understanding, architects will eventually develop structural intuition.[16] This intuition allows a designer to think about **structural behaviour** early in the design process, without needing calculations to understand how their design will react under load.[17] This intuition is developed with experience and experimentation that is facilitated by the use of the FEA software that simulates structural behaviour.[18] Through repeated use of the software, architects can learn to predict what the outcome of the structural analysis will be.[19]

A similar intuition may be developed with the use of **computational fluid dynamics (CFD) software** (Fig. 1.7), which in this thesis is used to describe the movement of wind. While it simulates fluid flow rather than structural behaviour, it provides similar advantages to the FEA software as it performs the engineering calculations to determine this fluid behaviour so that the user does not have to learn and perform these complicated calculations manually. The simulations that are generated by the software and visually represent the wind, rather than quantify it, are easier for users who are not trained in wind engineering to understand and interpret. Repeated use of the software allows the user to develop an understanding of wind behaviour, so that they are eventually able to predict the results of the simulation even without using the software. This allows them to make more informed design decisions earlier in the design process that consider the effects of wind on and around buildings.

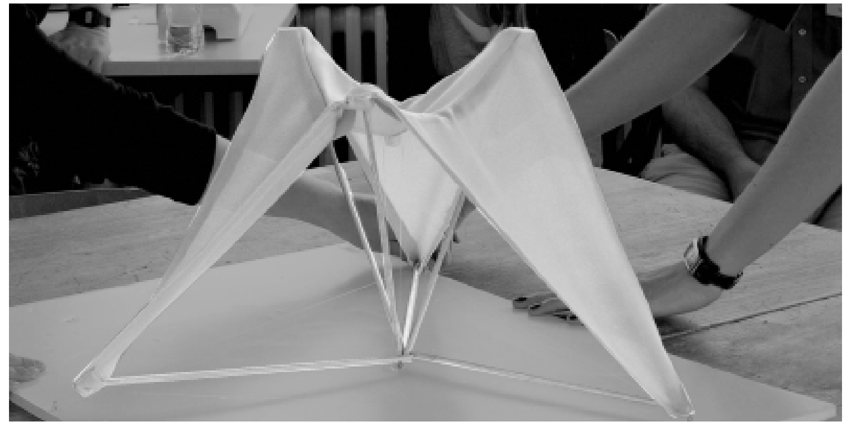


Fig. 1.5. Small-scale physical models demonstrate structural behaviour.

Finite element analysis (FEA) software
Software that evaluates the structural behaviour of an input model under input loading conditions and produces numbers, graphics and animations to convey this behaviour.

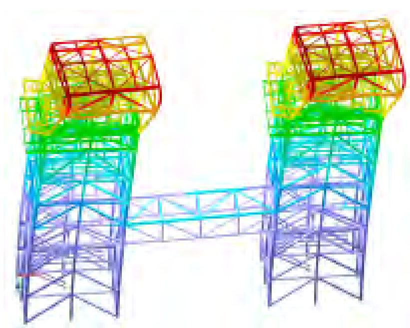


Fig. 1.6. Screenshot from finite element analysis software.

Structural design
The process of determining the form of a structure that will allow it to withstand subjected loads.

Structural analysis
The process of calculating the types and magnitudes of stresses and deformations in a structure subjected to loads.

Structural behaviour
The manner in which a structure acts or functions under loading conditions.

Computational fluid dynamics (CFD) software
Software that simulates the flow of fluids, including wind, around an input model and produces numbers, graphics and animations to convey this flow.

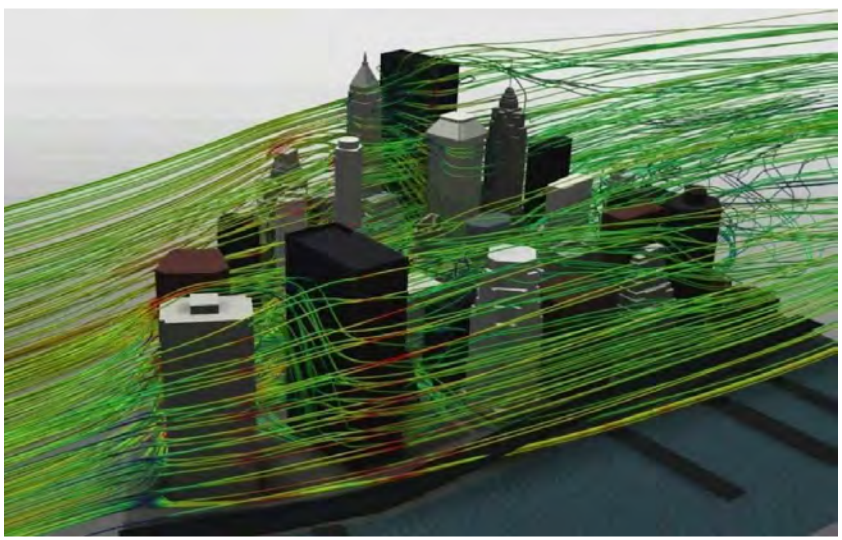


Fig. 1.7. Screenshot from computational fluid dynamics software.

The design method that is developed in this thesis integrates both wind and structural engineering considerations into early architectural design stages by pairing CFD software and FEA software. Software can be a valuable design tool for architects because it allows them to integrate engineering considerations into their current architectural practices, without having to acquire extensive engineering knowledge. It provides visualizations of wind patterns and structural behaviour, which are easier than numerical data for architects to understand and interpret, since they are trained in visual media. Software also provides architects with a means of quickly testing multiple design iterations in relation to these engineering considerations, because the software can perform engineering calculations and simulations much faster than if the architect were to learn and perform these calculations themselves. Repeated use of the software allows the user to gradually develop an intuitive understanding that allows them to predict what the results of the software analysis will likely be, which will eventually influence their design decisions even before the software analysis is run.

This design method does not intend for the architect to replace the structural or wind engineer. Instead, it equips the architect with the necessary knowledge and tools to design a building that considers wind effects and building aerodynamics in its initial form generation, which may be refined by the wind engineer in a later design phase. The method also allows the architect to design a building that accommodates a feasible structural system that the structural engineer can then easily adjust and detail. This approach allows the architect and engineers to work towards shared goals, thereby streamlining co-ordination between them. It also eliminates costly and time-consuming design revisions that can occur when wind effects and loading are only considered in the later stages of the design process. This method serves to re-integrate engineering and architectural design processes within the current working practices of architects and engineers.

DESIGNING WITH WIND

Throughout history, humans have tried to understand the seemingly arbitrary nature of the wind, as it both creates life and takes it away.[20] Wind makes the Earth habitable by cooling the equator and warming the poles,[21] it brings prosperity by carrying our ships and spinning our turbines, and it provides the welcome relief of a forgiving breeze on a hot day (Fig. 1.8). It can also damage our buildings and landscapes, carry dust storms and harsh winter chills, drive people mad with its relentless sound, and even kill people with its force (Fig. 1.9). Whether it comes as a blessing or a danger, we are at wind's mercy, so humans study how and why wind works the way it does so that we may decipher its arbitrary behaviour and be prepared to face it.[22]

Fig. 1.8. Wind can bring comfort and prosperity.

Fig. 1.9. Wind can also act destructively.

HOW WIND IS CREATED

The creation of wind begins with the sun, as the curve of the earth causes the sun's rays to strike the earth's surface directly at the equator and more obliquely at the poles (Fig. 1.10).[23] As a result, the sun's rays are distributed over a smaller area at the equator and a larger area near the poles, making the air hotter at the equator and cooler at the poles.[24] Since the molecules comprising hotter air are less dense than those that make up the colder air, this temperature difference creates air pressure differentials throughout the atmosphere.[25] These atmospheric pressure differentials cause wind, weather, and climate.[26]

Whenever there is a differential in the environment, nature has a tendency to want to equalize it.[27] Because the mass of the atmosphere is mostly constant, this equalization is achieved by re-distributing the atmospheric gases, and moving some of the molecules away from high pressure areas and into low pressure areas to balance the atmospheric pressure around the globe (Fig. 1.11).[28] This movement of atmospheric gases is the wind.[29]

Fig. 1.10. The sun's rays strike the Earth's surface at different angles.

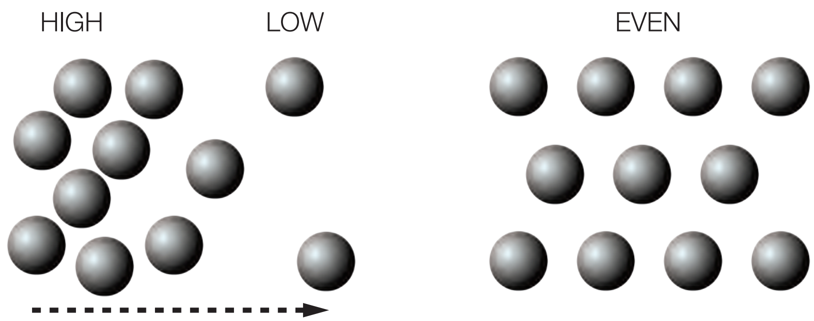


Fig. 1.11. Molecules move from high to low pressure areas.

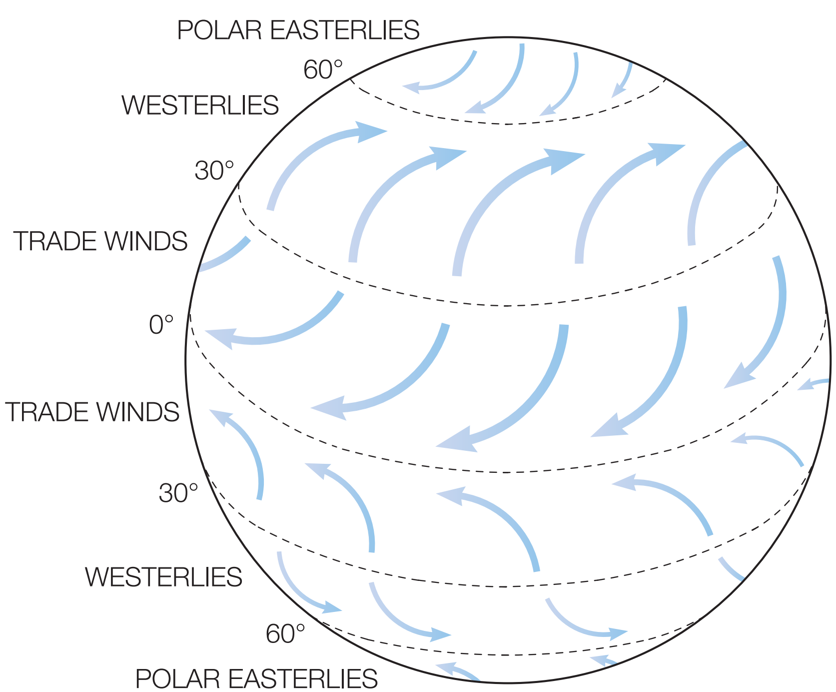


Fig. 1.12. Global wind patterns.

Wind speeds are determined by the magnitude of the pressure differential, as the larger the difference in pressure between the two areas, the faster the gases move between them.[30] Wind direction is determined by the locations of the high and low pressure areas in relation to each other, as air moves directly from the high pressure area to the low pressure area.[31] However, this straight line of movement is deflected by the Earth's rotation.[32] This deflection, coupled with the temperature differentials between the poles and the equator, create the global wind patterns.

GLOBAL WIND PATTERNS

At a global scale, wind and weather systems generally follow and repeat the same patterns.[33] At the equator, where the solar radiation is the most concentrated, the warmed air rises and creates an area of low atmospheric pressure closer to the Earth's surface.[34] This draws in air from the semi-tropical latitudes, but as this air moves towards the equator, the Earth's rotation from west to east causes the moving air to turn to the right in the northern hemisphere and to the left in the southern hemisphere until it is moving parallel to the equator.[35] This moving air is called the trade winds (Fig. 1.12),[36] whose consistency has been known and depended upon for sailing for hundreds of years.[37]

The trade winds are warmed at the equator, causing them to rise and drift towards the poles.[38] At about 30° latitude, they are cooled and sink back down towards the Earth's surface.[39] Some of this cooled air moves back to the equator again to become part of the trade winds, while some of it moves towards the low-pressure areas in the mid-latitudes.[40] As this air moves polewards, the Earth's rotation causes it to turn right in the northern hemisphere and left in the southern hemisphere.[41] These are the westerlies (Fig. 1.12),[42] which have also been exploited by sailors for hundreds of years for the colonization of, or trade with, foreign lands.[43] These regions have the most turbulent winds, as warm equatorial air and cool polar air meet here to cause gales and storms.[44]

While some of the air in the mid-latitudes forms the westerlies, some of the air higher up in the atmosphere moves back to the equator to join the trade winds, and some of the air near the Earth's surface moves further towards the poles.[45] At the poles, the cold air sinks to the ground to create areas of high pressure at the Earth's surface.[46] The air in these high pressure areas then moves back towards the equator, to the low-pressure areas next to the westerlies.[47] As this air moves it is deflected to the right in the northern hemisphere and to the left in the southern hemisphere to create the polar easterlies (Fig. 1.12).[48]

In between these wind patterns lie latitudinal bands of windless regions. The doldrums sit over the equator, usually extending about 5° to each side (Fig. 1.13).[49] In between the trade winds and the westerlies lies another band of calm air called the horse latitudes (Fig. 1.13).[50] These are still, low-pressure regions that are as well-known to sailors as the trade winds and the westerlies, but are avoided rather than exploited.[51]

HOW WIND CREATES CLIMATE

These global wind patterns move large air masses around the world.[52] Contained within these air masses is solar energy, so through the movement of the wind, much of the solar energy at the equator is transported towards the poles.[53] If wind did not occur to balance the distribution of the globe's solar energy, the equator would be too hot and the poles would be too cold for the survival of many species that inhabit the earth today.[54] The only habitable place on earth would be a small band in between the poles and the equator.[55] Through this distribution of air masses and solar energy, wind patterns create regions of weather and climate around the world.[56]

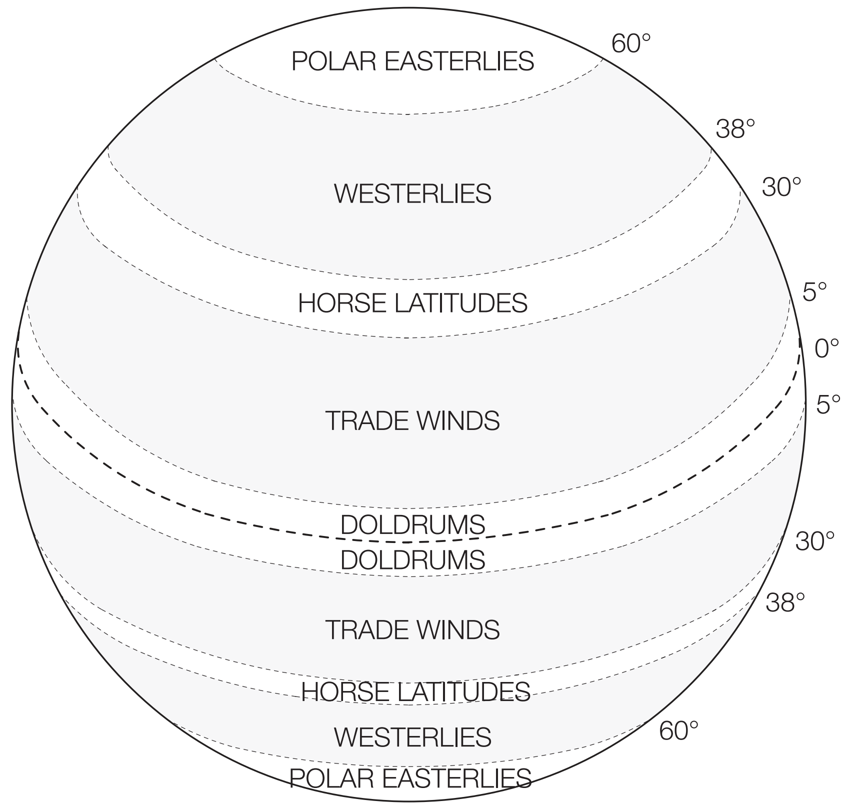


Fig. 1.13. Latitudinal bands.

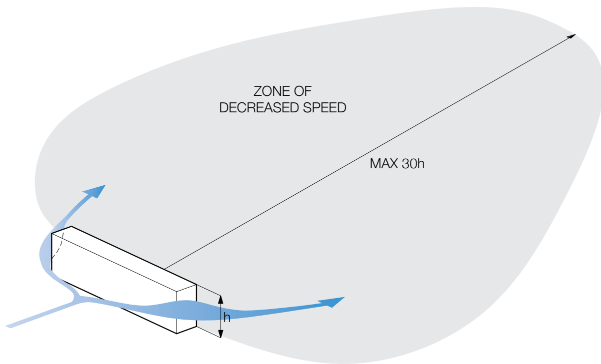


Fig. 1.14. Buildings shield leeward spaces from the wind.

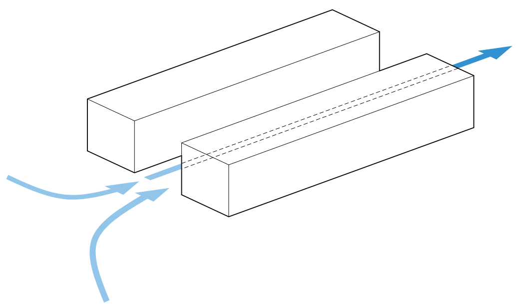


Fig. 1.15. Wind is channeled and accelerated between buildings.

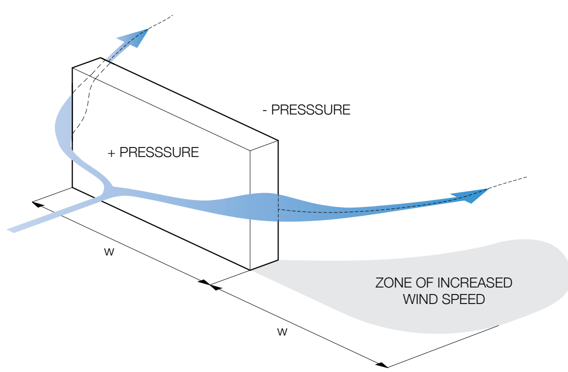
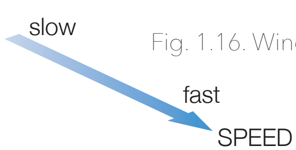


Fig. 1.16. Wind accelerates around corners.



BUILDINGS AFFECT WIND

Wind patterns are usually fairly consistent and predictable at a global scale, and if the Earth's surface was completely even, wind would flow smoothly and predictably at smaller scales as well.[57] However, this level of surface consistency is uncommon, except over oceans.[58] Small-scale surface variations, such as buildings, vegetation, and topography, alter local wind speeds and patterns and make local winds difficult to predict.[59]

When designing a building, it is important to understand how global winds affect the climate of the region, as well as how conditions around the building will alter local winds. Surface variations and temperature differentials are two factors that complicate wind at a local scale.

SURFACE VARIATIONS

As air flows over smooth surfaces, it is altered less than when it flows over surfaces with much variation.[60] Features that prevent the surface from being flat get in the way of the wind and complicate its flow by speeding it up, slowing it down, or creating turbulence. Such surface features include continents, topography, vegetation, buildings, and cities.[61]

Wind tends to slow down in cities because the surface roughness of the buildings slows down the wind flow, and because buildings shield adjacent leeward spaces from the wind (Fig. 1.14).[62] However, the wind can interact with buildings in ways that causes it to speed up in local areas. Buildings that are parallel to each other can create channels that increase the speed of the wind flowing between them (Fig. 1.15);[63] wind accelerates around building corners (Fig. 1.16)[64] and through building openings (Fig. 1.17);[65] and tall building faces that are exposed to oncoming wind can direct the higher-speed winds at higher elevations down the building face to the street level (Fig. 1.18).[66] In these ways, buildings and cities alter local winds and make them difficult to predict.

TEMPERATURE DIFFERENTIALS

Different landscapes radiate heat at different rates, and these local temperature differentials between two landscapes create pressure differentials that induce or alter wind.[67] Because land heats up faster than water, the resulting pressure differentials create wind at every coastline (Fig. 1.19).[68] Landscapes that radiate heat faster than others also cause wind at the boundary between them, such as the boundary between deserts, which radiate heat more quickly, and grasslands, which radiate heat more slowly.[69]

The temperature difference between urban and rural areas also influences local wind patterns to create an influx of wind into the city.[70] The heat conductivity of buildings and paved surfaces is much higher than that of soil and vegetation, so cities become warmer as they absorb more heat.[71] Underground drainage in the city also contributes to warmer city temperatures, as the energy that would be used to evaporate this water if it was above-ground, remains in the city in the form of heat.[72] These factors contribute to the urban heat island effect, which in turn affects the wind patterns between the city and the adjacent countryside.[73] Hot city air rises, creating an area of low pressure within the city closer to the ground level.[74] As a result, air from the surrounding rural, high-pressure areas blows into the city (Fig. 1.20).[75]

TORNADOES

In addition to the surface variations and temperature differentials that complicate wind, the tendency of air to form vortices also makes wind patterns less predictable.[76] One type of vortex is a tornado.[77] With their sudden formations,[78] unpredictable paths,[79] and blistering wind speeds,[80] they are a type of extreme wind that should be considered when designing buildings,[81] especially in tornado-prone areas.

A tornado is a column of air that rotates around a central point, and as the air gets closer to the centre, it rotates faster (Fig. 1.21).[82] The

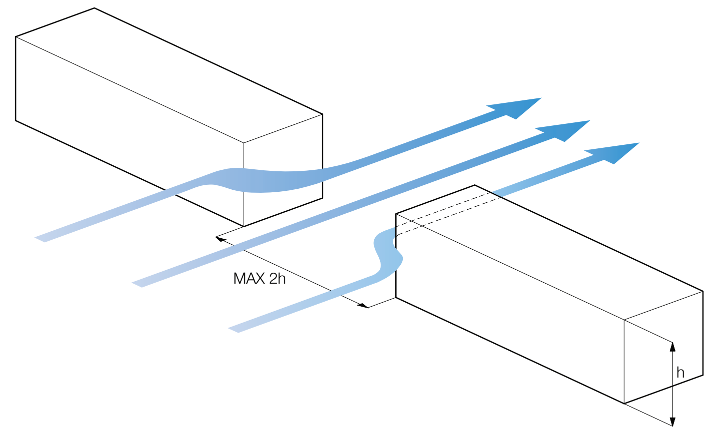


Fig. 1.17. Wind accelerates through openings between buildings.

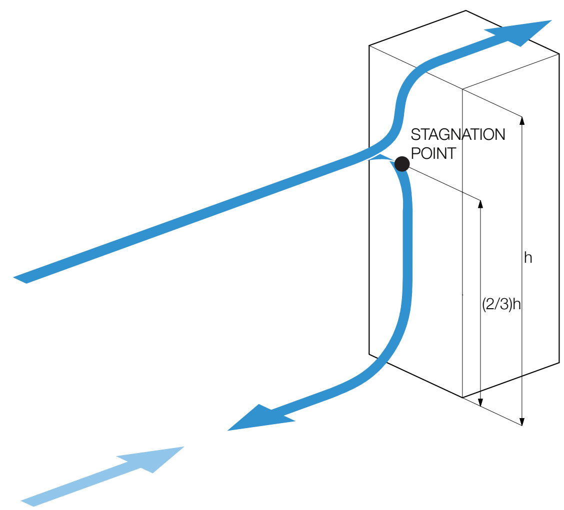
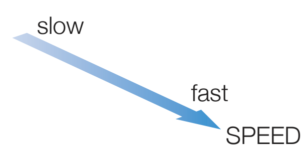


Fig. 1.18. Tall buildings direct high-speed wind down to street level.



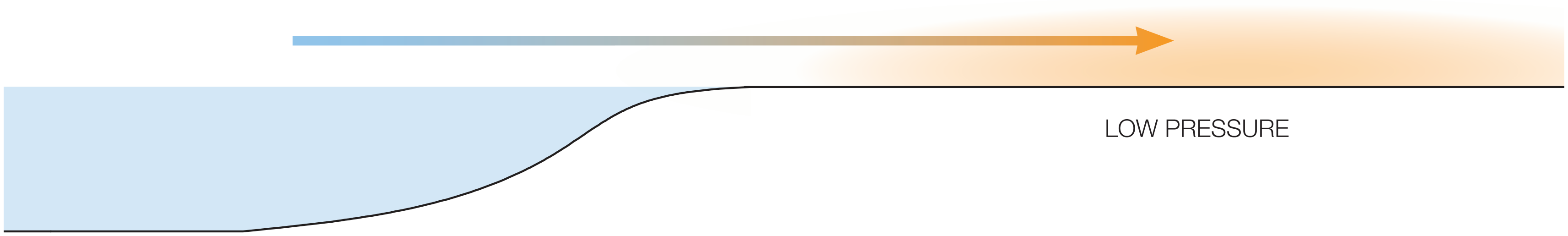


Fig. 1.19. Pressure differentials create wind at coastlines.

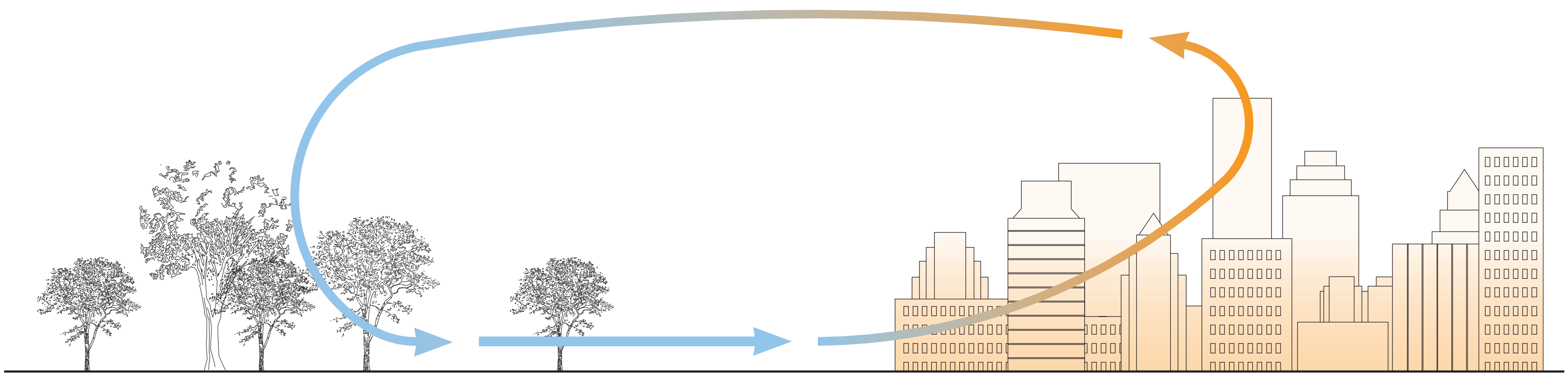


Fig. 1.20. Pressure differentials cause wind to blow into cities from surrounding rural areas.

wind speeds within these columns of air can exceed 450 km/h,[83] and as they move across the Earth's surface they can quickly and unpredictably change both speed and direction, even turning 180 degrees.[84] They are only made visible by the condensation that they contain, as well as the dust and debris such as soil, rocks, vegetation, and parts of buildings and infrastructure that they pick up along their way.[85] While the sequence of tornado formation is not clear, tornadoes occur when there is warm, humid air at ground level and cooler air at a higher elevation.[86] The air just above the Earth's surface must be warm enough to prevent the warm, ground-level air from rising into the cooler air above it.[87] If a sudden cold front comes in and moves this layer of warm air, the warm, humid air at ground level swiftly rises up into the colder air and causes a tornado to form.[88] This can happen suddenly and without warning, making tornadoes very difficult to predict.[89] A tornado warning usually comes only minutes before it strikes, which is usually insufficient time for the residents of the area to find shelter.[90] As a result, tornadoes can cause injury and death, as well as financial losses and substantial destruction of buildings and infrastructure.[91]

While some locations are more prone to tornadoes than others, tornadoes can occur all over the world.[92] Buildings located in areas that are prone to tornadoes should ideally be designed to withstand their extreme winds.[93] However, because tornadoes are low-probability events, most buildings are not specifically designed to resist the damage that they can cause, although these buildings' structures can usually withstand the damage even if their cladding cannot.[94] There are three main ways in which tornadoes may inflict damage upon buildings. First, the extreme winds exert high wind forces on buildings that can destroy their cladding and strain their structural systems.[95] These forces may be resisted by stiffening the building's structural system and using resilient construction for the roof and facades.[96] Second, tornadoes cause rapid drops in the exterior air pressure.[97] Because these pressure drops occur in a matter of seconds, buildings do not have time to adjust to the pressure difference between the interior and exterior.[98] This

Fig. 1.21. A tornado is a rotating column of air.

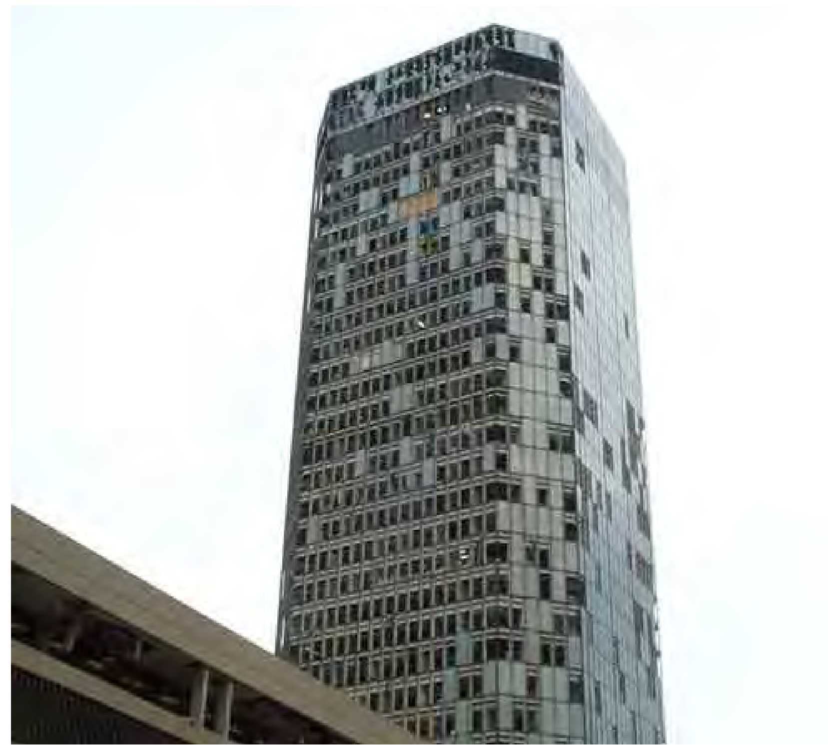


Fig. 1.22. Cladding is often damaged by tornadoes.

Fig. 1.23. When building facades are damaged, the interior is exposed.

causes the roof and walls to be blown outwards.[99] This could be prevented with resilient construction that allows roofs and walls to resist increased pressure loads, or by venting between the building interior and exterior.[100] Buildings may also be damaged during tornadoes by debris that is picked up by the tornado and hits the buildings.[101] The damage caused by debris may be reduced with resilient building construction to allow buildings to better withstand the impact.[102] Building roofs and facades are often damaged by tornadoes in these three ways, as the cladding is not designed to as high a factor of safety as the structure (Fig. 1.22).[103] When the cladding is damaged, the building interior is exposed to the outside and is also damaged by the high winds and flying debris (Fig. 1.23).[104] Because of the ways in which tornadoes can affect buildings, these extreme winds should be a consideration during building design.

DESIGNING WITH WIND

Wind has a large impact on the built environment.[105] It is also the most dynamic climate parameter that architects must work with.[106] The prominence and unpredictability of wind, especially at the scale of a building,[107] provides an extreme context within which to test the integration of architecture, wind engineering, and structural engineering through the development of a design methodology. Wind effects on buildings are constantly changing, so buildings may be designed to resist these fluctuating wind loads, as well as alter its patterns to create desirable wind conditions around the building. As such, the methodology that is developed in this thesis harnesses the productive nature of the wind, while resisting its destructive nature. We may be at wind's mercy, but if we can understand the wind, we may manipulate it to serve our purposes.

CFD SOFTWARE

HOW IT WORKS

Computational fluid dynamics (CFD) uses complex equations to describe the movement of heat or fluids (such as air and water) in and around solid objects[108] over time.[109] For the purpose of this thesis, CFD is used to simulate wind. Complex differential equations are used to describe this fluid movement, but their complexity requires that they be solved with a CFD code as it is impossible to solve them by hand.[110] The code first subtracts the building model (Fig. 1.24) from the total volume of the digital model space.[111] It then analyzes the remaining volume, which is the empty space around the building model (Fig. 1.25).[112] This space is then divided into small boxes (Fig. 1.26), and the motion of the fluid within each box, as well as how it interacts with the fluid in the neighbouring boxes, is calculated using the differential equations.[113] These calculations are then repeated for each box and for subsequent moments in time, to simulate the movement of the fluid within the entire space around the building model.[114] The simulation parameters, which for this thesis are wind speed and direction, are input by the user before the simulation is run.

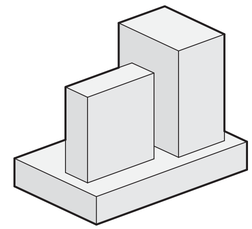


Fig. 1.24. Digital building model.

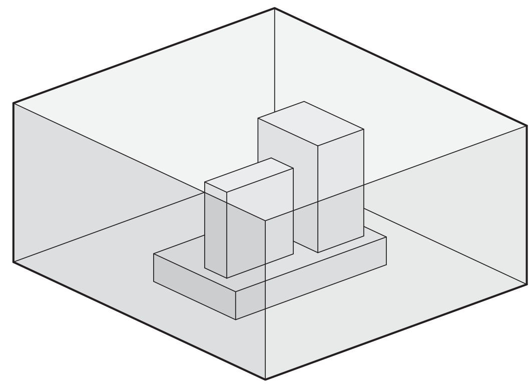


Fig. 1.25. Remaining space around the digital building model.

ACCURACY

The accuracy of a CFD simulation depends on several factors. Some codes are designed to be more accurate than others, but because they are inherently more complex, the hardware requirements are more intensive and it is also often necessary for a CFD specialist to run them.[115] The accuracy also depends on the grid resolution that is set either manually by the user, or automatically by the software.[116] A higher grid resolution will yield more accurate simulations as it divides the volume around the model into smaller boxes, but the trade-off for this increase in accuracy is an increase in computing time.[117] The accuracy of the simulation is also affected by the extent to which the surrounding surface features are modeled.[118] These surface features can have such a substantial influence on the behaviour of the fluid surrounding the model that without considering their impact,

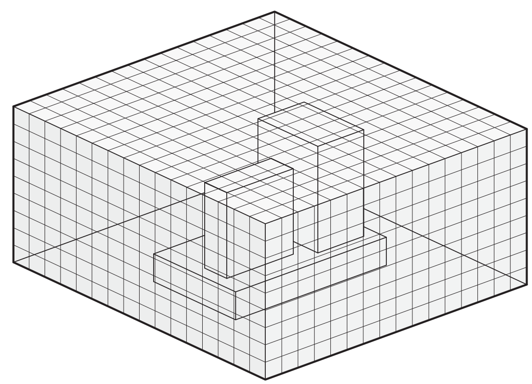


Fig. 1.26. Remaining space divided into small boxes.

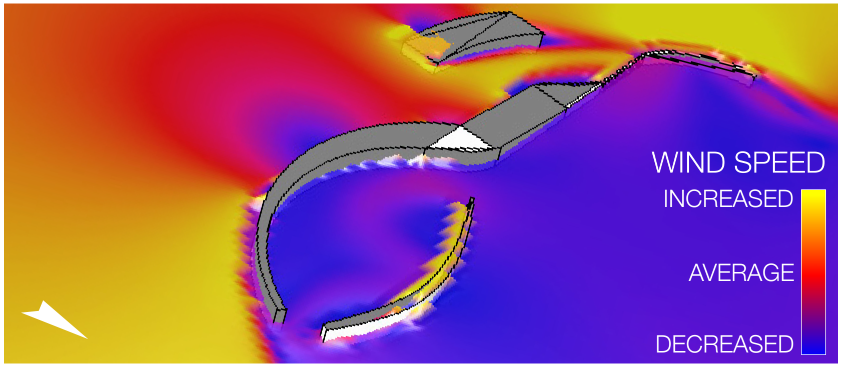


Fig. 1.27. Wind speed data slice.

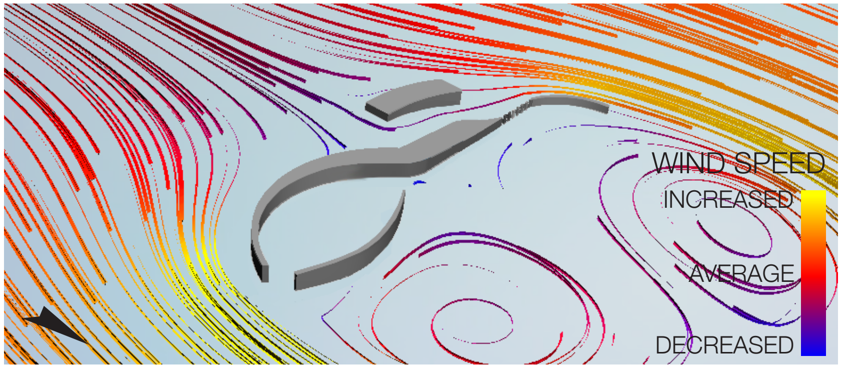


Fig. 1.28. Flow line animation.

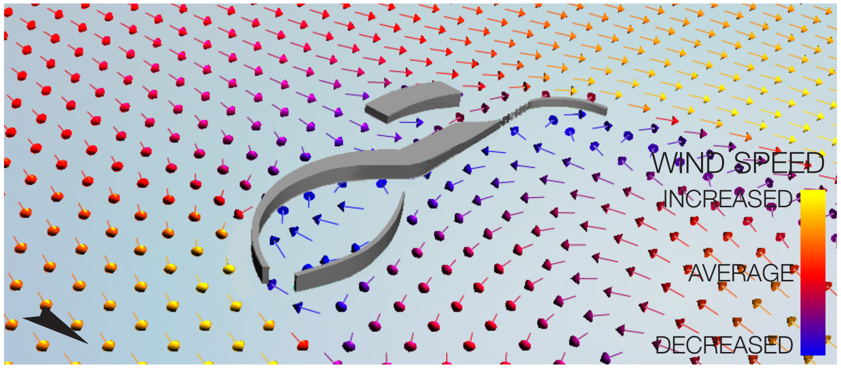


Fig. 1.29. Vector field.

the simulation results could be inaccurate. However, larger, more complex models that include these surrounding features also increase the computing time required to run the CFD simulation.[119]

OUTPUT

For the purpose of this thesis, CFD software is used to simulate and represent the flow of wind around a building. The software provides information about wind speed, patterns, and pressure, through a variety of visual output styles from which the user may choose to display the required information. The following visual output styles may be obtained from the CFD software that is used in this thesis:

WIND SPEED DATA SLICE
Depicts the variation in wind speed around the building model within a single horizontal or vertical plane, represented by the colour variation of the data slice (Fig. 1.27).

FLOW LINE ANIMATION
Animates the wind flow, conveying wind patterns with the movement of the flow lines and representing wind speed with the colours of the flow lines (Fig. 1.28). Flow lines may be animated in a single horizontal or vertical plane, or throughout the 3D volume around the building model.

VECTOR FIELD
Conveys wind patterns with the direction of each arrow, and represents wind speed with the colours of the arrows, within a single horizontal or vertical plane (Fig. 1.29)

WIND PRESSURE DATA SLICE
Depicts the variation in air pressure around the building model within a single horizontal or vertical plane, represented by the colour variation of the data slice (Fig. 1.30). It should be noted that wind suction is represented as negative wind pressure, so larger magnitudes of wind suction are represented by colours at the bottom of the legend in Fig. 1.30, and larger magnitudes of positive

wind pressure are represented by colours at the top of the legend. Wind pressure of minimum magnitude is therefore represented by colours in the middle of the legend.

SURFACE WIND PRESSURE GRADIENT
Depicts the variation in wind pressure acting over the surface of the building model, represented by the variation in the colours applied to the model's surface (Fig. 1.31). The legend in Fig. 1.31 conveys the same information as the legend in Fig. 1.30, which is described above.

ARCHITECTURAL APPLICATIONS

CFD simulations of wind flow are useful in architectural applications, as they can determine pressure loads on facades[120] and structures, simulate the flow of air within buildings for HVAC studies, and simulate wind conditions around buildings for studies of pedestrian comfort and pollutant dispersion.[121] However, within current architectural practice, these simulations are mainly used for verification of the design at a later stage, and do not usually inform the initial design of the building.[122] They are also often performed by CFD specialists who work with a consulting engineer,[123] who then makes design recommendations to the architect based on the results of the simulation.[124] Rarely is the architect directly involved in the CFD simulation process.[125] However, engineer Ziad Boutanios, who specializes in CFD, believes that there is potential for architects to be more directly involved in this process, through the use of simpler codes that they may run themselves to obtain visualizations of general wind trends.[126] This thesis seeks to do this by selecting and appropriating existing CFD software, so that architects can run the simulations themselves and obtain qualitative wind information early in the design process that informs the schematic design of their buildings. The visual representation of the wind that may be obtained from the CFD software makes it easier for architects who are not trained in wind engineering to understand and interpret the results, and allow the results to inform their building designs.

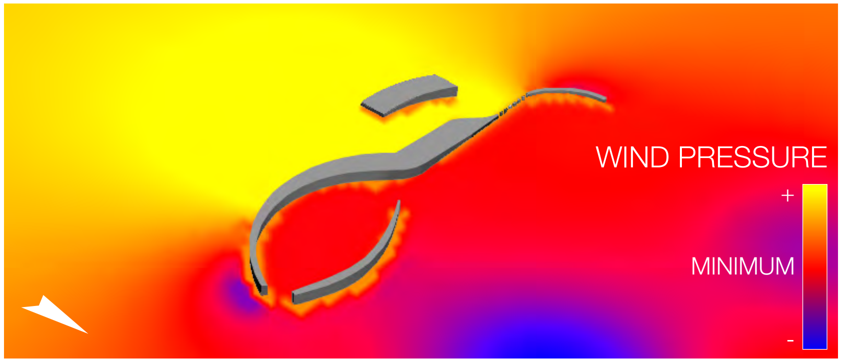


Fig. 1.30. Wind pressure data slice.

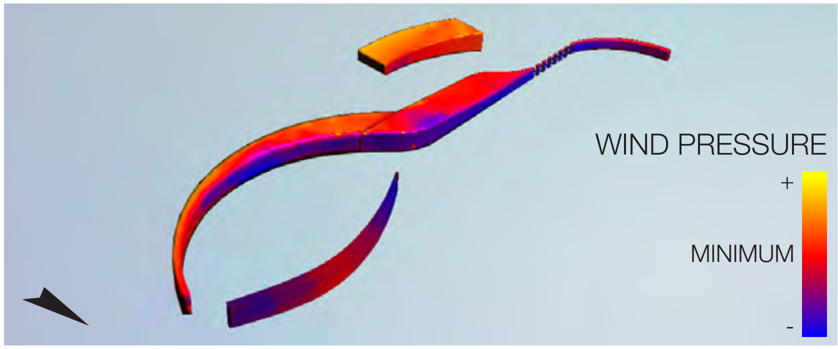


Fig. 1.31. Surface wind pressure gradient.

FEA SOFTWARE

HOW IT WORKS

Finite elements
Small pieces into which a digital model is divided to be analyzed by FEA software.

Meshing
The process of representing a physical entity with finite elements, by breaking it down into smaller pieces to re-build it as a set of points, edges, and faces that approximate the original model.

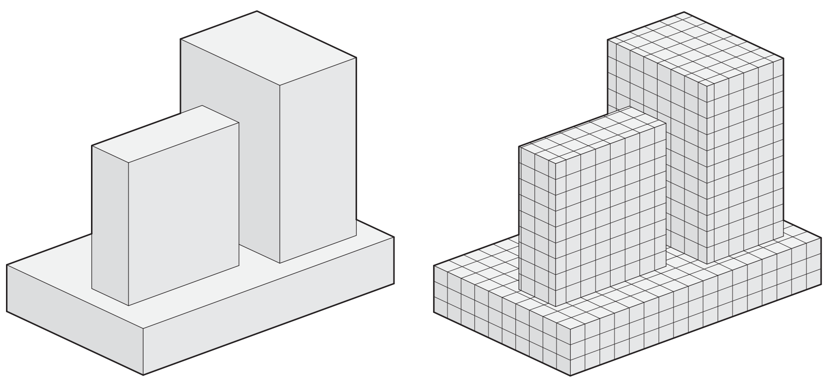


Fig. 1.32. A digital model is broken down into finite elements.

Mesh
A set of finite elements made up of points, edges, and faces that approximate the original model.

Finite element analysis (FEA) is a computerized method that predicts and simulates how a digital model will react to applied forces.[127] The software breaks down the digital model into small pieces called **finite elements** and analyzes the behaviour of each of these elements under the input loading, restraints, and material properties.[128] The assembly of the behaviour of all of the finite elements conveys the global structural behaviour of the entire digital model.[129] For the purpose of this thesis, FEA software is used to simulate and visualize the effects of forces on building structural systems.

In order to run finite element analysis on a digital model, steps must be taken to make the model into a finite element (FE) model that is defined by its geometry, its constraints, its material properties, and the applied loads.[130] To create an FE model, a digital model is first made of the geometry to be analyzed.[131] Within the FEA software, the user then specifies the types, magnitudes and locations of the applied loads, the locations of the restraints, and the properties of the material out of which the full-scale model would be made.[132] Finally, the model must be meshed to turn it into a FE model.[133] **Meshing** is the process of representing a physical entity with finite elements,[134] by breaking down the model into smaller pieces[135] to re-build it as a set of points, edges, and faces that approximate the original model (Fig. 1.32).[136] This set of finite elements is called a **mesh**.[137] While there are theoretically no limits on the shapes that these finite elements may be, in practice only simple shapes are used.[138] They may be one-dimensional lines, two-dimensional triangles or quadrilaterals, or three-dimensional tetrahedrons or hexahedrons.[139] Because the finite elements are simply-shaped pieces, they are only able to approximate the more complexlyshaped original model to a certain degree of accuracy that depends on the size of the finite elements,[140] unless the original model was already built as a mesh.[141] Splitting the model into these small, simply-shaped elements allows them to be analyzed with simple equations, rather than using complex equations on the entire, more complex digital model.[142] The meshing process can be time-consuming and complicated, and while most FEA programs require the user to carry out this process manually, this thesis uses a program that performs this step automatically. Once the mesh is created, the analysis is run to determine how the mesh will behave under the input loads, constraints, and material properties.

After the analysis has been run, the designer looks at the results to find any areas of the model that are structurally inadequate, and then alters the digital model to improve its performance under load.[143] The FEA process is then repeated with the altered digital model to ensure that its structural performance has adequately improved with the changes.[144]

OUTPUT

When a force is applied to a material, the force produces stress within that material that causes it to deform.[145] This deformation is seen in strain, which measures change of length per unit length,[146] and displacement, which describes the movement of each point of the model under the force.[147] Stress, strain, and displacement are the three types of output that are available from the FEA software that is used in this thesis.

STRESS

Stress is a quantity that describes all the internal forces acting within a body of material, and is measured in units of force per area.[148] FEA software represents stress as colour gradients over the model surface, with the colour representing the amount of stress that the material experiences at that point under load. The two basic

Stress
A quantity that describes all the internal forces acting within a body of material.

Fig. 1.33. The particles of a material under tensile stress get pulled apart.

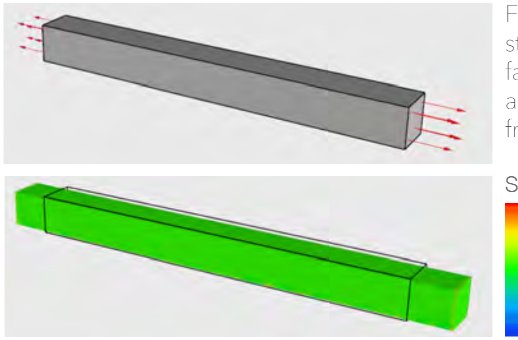


Fig. 1.34. Block under tensile stress with 1 kN loads on end faces (top); stress distribution and exaggerated deformation from FEA software (bottom).

STRESS
1 450 Pa Tension
470 Pa Tension

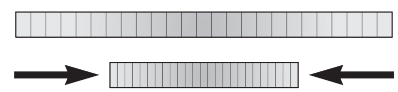


Fig. 1.35. The particles of a material under compressive stress get pushed together.

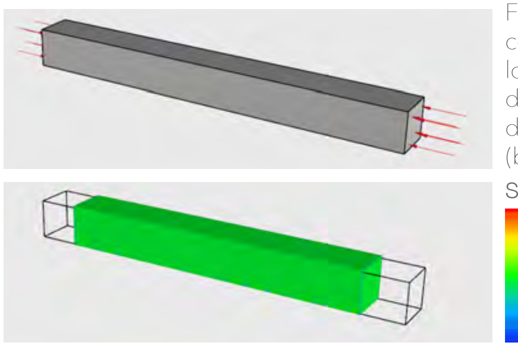


Fig. 1.36. Block under compressive stress with 1 kN loads on end faces (top); stress distribution and exaggerated deformation from FEA software (bottom).

STRESS
470 Pa Compression
1 450 Pa Compression

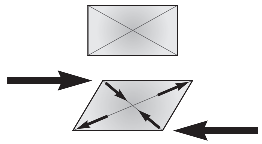


Fig. 1.37. The particles of a material under shear stress slide relative to each other.

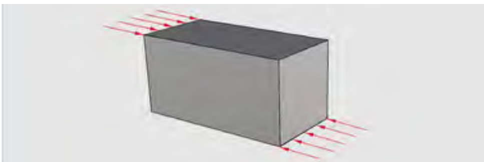
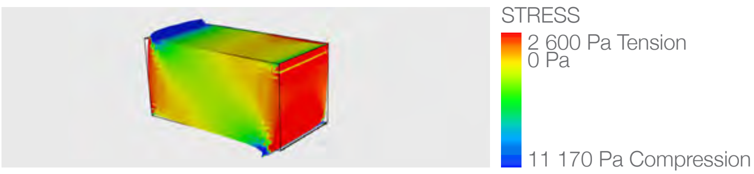


Fig. 1.38. Block under shear stress with 1 kN loads on edges (top); stress distribution and exaggerated deformation from FEA software (bottom).



Due to software limitations that restrict how restraints are specified, the deformation shown in Fig. 1.38 is not entirely accurate.

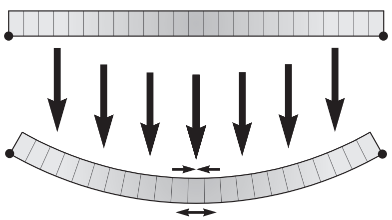


Fig. 1.39. The particles of a material under bending stress shorten on one side and elongate on the other side.

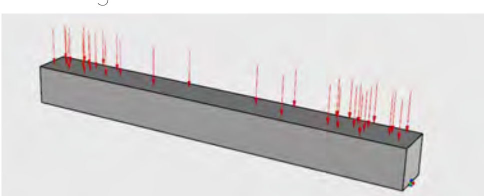


Fig. 1.40. Block under bending stress restrained on bottom edges of end faces with 1 kN load on top face (top); stress distribution and exaggerated deformation from FEA software (bottom).

states of stress are tension and compression.[149] When a material experiences tensile stress, its particles tend to be pulled apart (Fig. 1.33, Fig. 1.34), whereas under compressive stress, the particles tend to be pushed together (Fig. 1.35, Fig. 1.36).[150] All complex states of stress are combinations of tension and compression,[151] such as shear stress, in which the particles of the material slide relative to each other[152] as one cross-section diagonal lengthens in tension and the other shortens in compression (Fig. 1.37, Fig. 1.38),[153] or bending stress, in which the material curves under load and the fibers shorten in compression on one side and elongate in tension on the other side (Fig. 1.39, Fig. 1.40).[154]

STRAIN

Strain describes the deformation in a direction that is caused by stress, and is a unitless quantity that is measured in change in length per unit length.[155] FEA software represents strain as colour gradients over the model surface, with the colour representing the amount of strain that each part of the model would experience under load. Tensile strain is the elongation of a unit length of material (Fig. 1.41, Fig. 1.42), whereas compressive strain is the shortening of a unit length of material (Fig. 1.43, Fig. 1.44).[156]

DISPLACEMENT

Displacement describes where and by how much a point of a body moves while the body experiences stress, and is measured in units of length.[157] FEA software represents the displacement of each point of a model as a colour gradient over the model's surface, with the colour at any given location representing the amount of displacement of that point. This displacement of each point causes the body as a whole to undergo **deformation**,[158] unless all of the points displace the same amount.[159] In this case, the body translates, or moves, rather than deforms.[160] The FEA software can create animations of the model deforming under load as each of its points is displaced, to assist the user in visualizing the model's structural behaviour. A body under tensile stress deforms

Strain
A quantity that describes deformation in a direction.

Fig. 1.41. Tensile strain is the elongation of a unit length of material.

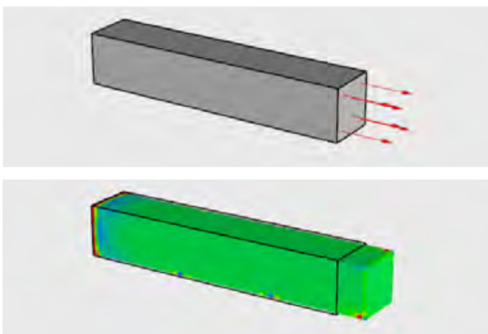


Fig. 1.42. Block with left face restrained and 1 kN load on right face (top); resulting tensile strain and exaggerated deformation from FEA software (bottom).

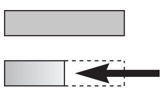


Fig. 1.43. Compressive strain is the shortening of a unit length of material.

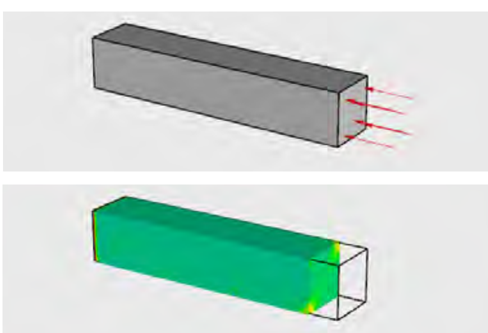
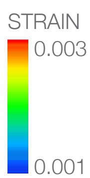


Fig. 1.44. Block with left face restrained and 1 kN load on right face (top); resulting compressive strain and exaggerated deformation from FEA software (bottom).



Displacement
A measure of where and by how much a point of a body moves while the body experiences stress.

Deformation
The action of a body changing shape as the points within the body displace different amounts.

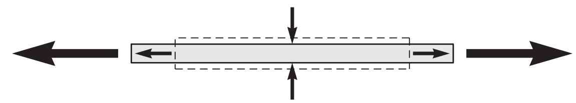


Fig. 1.45. A body under tensile stress elongates in the direction of the force and shortens in the direction perpendicular to the force.

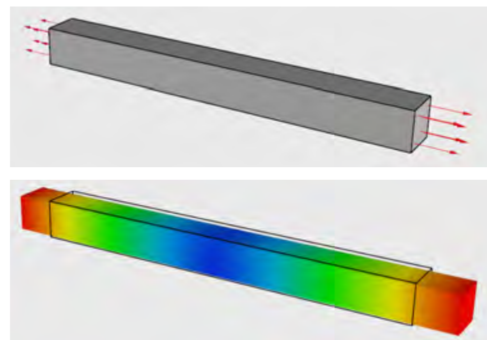
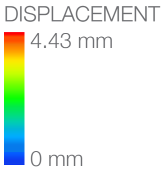


Fig. 1.46. Block under tensile stress with 1 kN loads on end faces (top); displacement of each point and exaggerated deformation from FEA software (bottom).



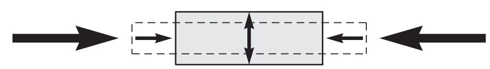


Fig. 1.47. A body under compressive stress shortens in the direction of the force and elongates in the direction perpendicular to the force.

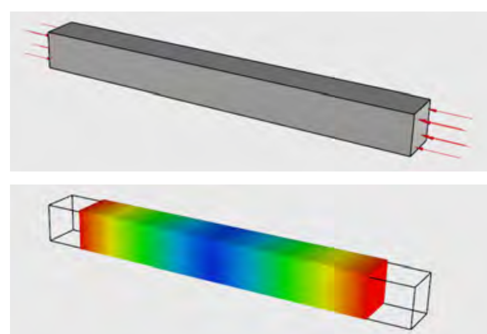
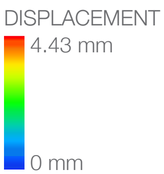


Fig. 1.48. Block under compressive stress with 1 kN loads on end faces (top); displacement of each point and exaggerated deformation from FEA software (bottom).



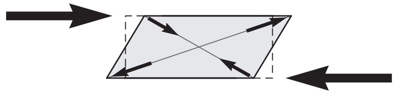


Fig. 1.49. A body under shear stress lengthens along one diagonal and shortens along the other diagonal.

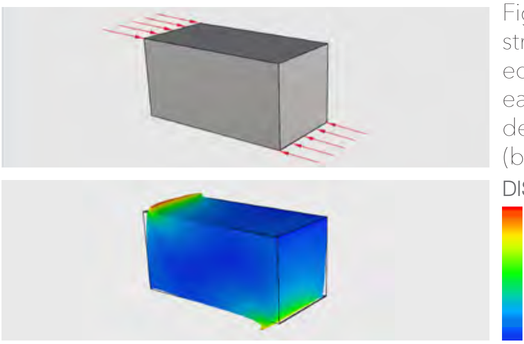


Fig. 1.50. Block under shear stress with 1 kN loads on edges (top); displacement of each point and exaggerated deformation from FEA software (bottom).

DISPLACEMENT
8.68 mm
0 mm

Due to software limitations that restrict how restraints are specified, the deformation shown in Fig. 1.50 is not entirely accurate.

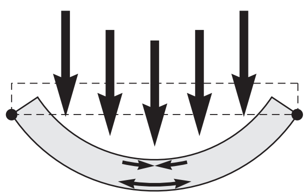


Fig. 1.51. A body subject to bending elongates on one side and shortens on the other side.

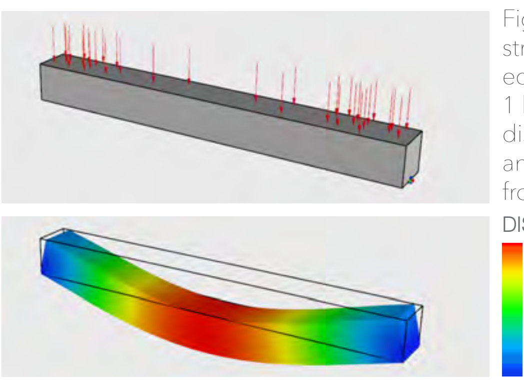


Fig. 1.52. Block under bending stress restrained on bottom edges of end faces with 1 kN load on top face (top); displacement of each point and exaggerated deformation from FEA software (bottom).

DISPLACEMENT
18.73 mm
0 mm

as it elongates in the direction of the force and shortens in the direction perpendicular to the force (Fig. 1.45, Fig. 1.46), while a body under compressive stress shortens in the direction of the force and elongates in the direction perpendicular to the force (Fig. 1.47, Fig. 1.48).[161] While in shear, the cross-section of a body lengthens along the diagonal that is in tension and shortens along the diagonal in compression,[162] causing a rectangular cross-section to deform into a parallelogram (Fig. 1.49, Fig. 1.50).[163] When a body is subject to bending, the material on one side elongates in tension while the other side shortens in compression (Fig. 1.51, Fig. 1.52).[164]

ACCURACY

The accuracy of FEA depends on the size of the finite elements.[165] The smaller they are, the more accurate the analysis will be.[166] Finite elements usually have straight sides, so when they are used to approximate a curved or more complex form, a finer mesh with more, smaller finite elements is a better approximation of the original form than one with fewer, larger finite elements (Fig. 1.53).[167] As the number of finite elements increases and their size consequently decreases, the finite element solution converges to the exact solution, which is approached asymptotically.[168] However, while a finer mesh provides more accurate analysis results, it also uses more of the computer's memory and requires longer solving times.[169]

The size that the finite elements should be in any given analysis is decided by the person running the analysis, and depends on both the model being analyzed as well as the type of information that the user wants to obtain from the analysis.[170] There is no rule or method that may be used to determine element size;[171] rather, it is determined with the user's engineering knowledge and experience.[172] It is best practice in engineering to use the simplest model and run the simplest analysis that will still provide the required information and level of accuracy.[173] The user will often run several finite element analyses on the same model, specifying different element sizes each time, to determine which size provides an adequate level of accuracy without taking too long to compute.[174] Engineering knowledge can also inform element size, as the user could specify a coarse mesh over most of a model with a finer mesh around a small area of the model that they know will have a large impact on the structural behaviour of the model as a whole (such as an opening around which there would be a high stress concentration).[175] This provides a more accurate analysis at the location where a high level of accuracy is the most important, without taking a lot of time to compute the results over the rest of the model where the same level of accuracy is not needed.

While architects who use FEA software should follow the engineering practice of using the simplest model and the largest element size that will still provide the required level of accuracy, they may not posses the same knowledge and experience as engineers to be able to determine what that size would be. The FEA software that is used in this thesis automatically meshes the model, so that the architect does not have to execute this process themselves. However, it is still beneficial for the architect to understand how to determine an appropriate element size, especially if they would like to use different FEA software in which they would need to mesh their models manually. To find the appropriate element size for a given problem, architects could run two finite element analyses on the same model, but specify a mesh for the second analysis that contains twice the number of finite elements as the mesh for the first analysis.[176] If the two analyses have similar results, the architect can be confident that the coarser mesh is adequate to obtain accurate

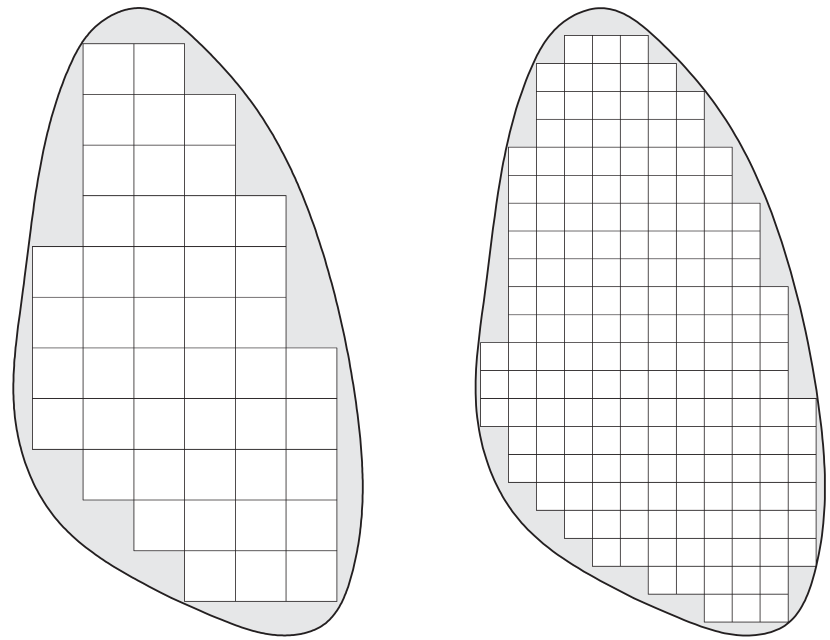


Fig. 1.53. Smaller finite elements (right) provide a better approximation of a form than larger finite elements (left).

information.[177] If, however, the two analyses produce different results, this indicates that the finer mesh is necessary to obtain accurate information.[178] This allows the architect to determine the appropriate element size by comparing the visual output from the analyses, rather than relying on engineering knowledge to make this decision.

Specifically addressing the use of FEA in wind loading applications, the software used in this thesis assumes that the forces applied to the model are static, and that they increase slowly and then remain consistent.[179] This is contrary to the dynamic nature of wind loading, which can change suddenly and intensely. The software therefore disregards the dynamic effects of wind and instead simulates average wind loads.

ARCHITECTURAL APPLICATIONS

Most FEA software is intended to be used by engineers to analyze and improve the structural properties of an existing model.[180] It is used as a design tool, as FEA is run continuously throughout the design process so that the engineer can understand the structural implications of each design iteration.[181] In the design method developed in this thesis, FEA is also used as a design tool to test and refine iterations of building structure, much in the same way as it is used by engineers. The FEA software is used to simulate and represent the effects of combined wind and gravity loading on the building's form and structural system. Graphics and animations of structural behaviour are used instead of numerical data, as they are more easily understood by architects who are not trained in structural engineering. However, because architects are not trained as extensively in structural concepts as engineers, they need to develop a structural understanding to ensure that they are able to interpret the FEA results correctly.

Wind speed and turbulence are relatively easy concepts for architects to understand, as everyone has felt the wind. This means that once the wind is visualized by CFD software, the architect running the simulation can interpret the results and understand what they mean by drawing on their own experience of the wind. FEA software, however, simulates structural behaviour and produces results of stress, strain and displacement, which are more abstract concepts in which architects are not extensively trained and with which they may not have direct experience. While it can be simple for architects to run the analysis, they must have an understanding of these concepts to be able to interpret the results of the analysis, and know how they should adjust the model accordingly to improve its structural performance. This may be achieved through repeated use of the FEA software.[182] Software has a lot of potential to allow architects to work within the realm of structural engineering, as it means that they do not need to have extensive structural knowledge to be able to test many design iterations. Through these tests, they can learn what the analysis results mean and how changes to the model affect the results. With experience and experimentation facilitated by the FEA software, the architect will eventually develop structural intuition that will allow them to consider structural behaviour earlier in the architectural design process.

SOFTWARE SELECTION

Most CFD and FEA programs are intended for use in engineering, rather than architectural, applications. This design method selects software that can be adapted for use in architectural applications, and uses them in a way that is appropriate for the initial architectural design stages. To ensure that this design method is accessible to architects, many types of CFD and FEA programs were researched to determine which are most appropriate for use in this design method.

REQUIRED CRITERIA

In order for a CFD or FEA software to be considered for use in this method, it has to meet the following required criteria:

1. 3D-MODELING SOFTWARE COMPATIBILITY
   The software must either be a plug-in for, or run files from, 3D-modeling programs that are commonly used by architects or geared towards architectural, rather than engineering, applications. Rhinoceros and Revit are two such programs, so the chosen CFD and FEA programs must be compatible with at least one of these two programs. Rhinoceros can be used to create initial building massing models on which wind studies may be performed. The building can then be modeled in Revit to continue to develop the project and its wind studies in more detail through the later project phases. Executing the design method with these two programs eliminates the need for architects to learn new 3D-modeling software in addition to the CFD and FEA software, making the design method more accessible to architects.

2. FREE EDUCATIONAL LICENSE
   The software must be free for students, to encourage its use in a studio setting. This would allow students to learn these programs while in school, so that they would be proficient in them when seeking jobs after graduation. This criteria would make it more feasible for architectural firms to adopt these programs into their current working methods, since it would be easier to find employees who know how to use them. It is advantageous if the program is also free for commercial use; however, since architectural firms have greater financial resources than students, and since very few programs are free for commercial use, it is not a requirement.

EVALUATION FACTORS

After the elimination of software that did not meet the above criteria, the remaining programs were evaluated based on the following factors to determine which should be used in this design method:

1. EASE
   It is advantageous if the software is easy to learn, as architects will be more inclined to learn it. This also allows them to

implement the design method sooner, instead of spending more time learning a complex software.

2. SPEED

It is advantageous if the software is able to quickly provide the user with results. This includes considerations of how fast a model can be set up for evaluation, any geometry clean-up that the software might require, and how long it takes the software to process a result. The faster the program can work, the more design iterations can be tested and refined.

3. ACCURACY

It is advantageous if the software provides accurate analysis results. However, this factor is the least valued, as for the purposes of initial design development, it is more advantageous to use a program that is easy to learn and that quickly tests multiple design iterations, rather than use one that is complex but provides completely accurate data. For example, it is better for this method to employ a CFD program that is fast but less accurate, since no CFD software is as accurate as a physical wind tunnel. The chosen CFD programs therefore simulate general patterns of wind flow, but are not relied upon for quantitative results. It is also preferable to select an FEA software that is easy to use, rather than one that provides accurate results but is too complex to be feasibly integrated into the initial design stages. The purpose of this thesis is to develop a methodology that will become more accurate as CFD and FEA software is improved, so accuracy is not as important at this stage of the method's development.

4. 3D-MODELING FUNCTION

It is advantageous if the software includes 3D-modeling functions, because once the CFD or FEA results are obtained, the design can be adjusted accordingly within the same program. This eliminates the need to switch programs to make the changes to the digital model, and then re-export the model to run the evaluation. This speeds up the design method.

5. PRICE

It is advantageous if the software is inexpensive, as it is more feasible that architectural firms would integrate a design method that uses inexpensive software into their working practices.

SOFTWARE SELECTION

The following CFD and FEA programs were researched and considered in relation to these five factors. The diagrams rank each software in terms of the factors, to determine which should be used in this design method. The larger the area of the shaded polygon, the more advantageous the program is for the purpose of this thesis.

VASARI

Software Type
CFD
Made By
Autodesk
Software Compatibility
Rhino files | Revit files
Intended Use
This program is much like a simplified version of Revit, with a similar interface and similar tools. It was designed to be used for initial massing, environment, and energy studies of architectural projects.[183] After the massing has been refined according to these studies, the model can be easily exported to Revit for continued project development. The environmental tools include a wind tunnel simulator that allows users to visualize the air flow around digital 3D models. It simulates only major qualitative wind trends, and is intended to provide insight into wind patterns at early stages of building massing.[184] Although the speed with which results can be obtained is useful during early project stages, the designer should be aware that the CFD analysis is not always especially accurate. However, this does not negate the usefulness of these results to depict general wind trends. Vasari can run files from Rhinoceros and Revit, and also includes a 3D-modeling function within the program.[185]

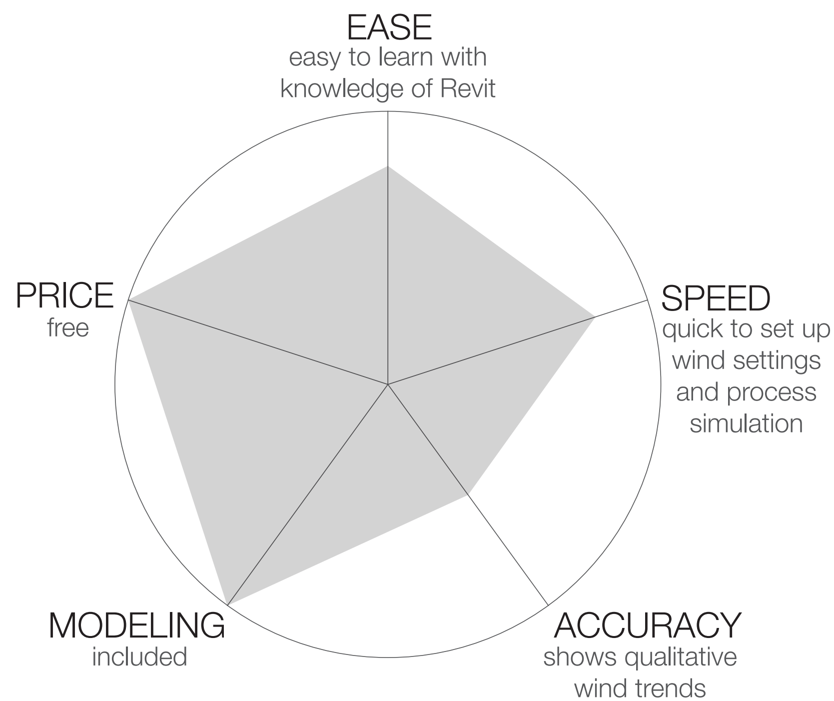


Fig. 1.54. Vasari software ranking diagram.

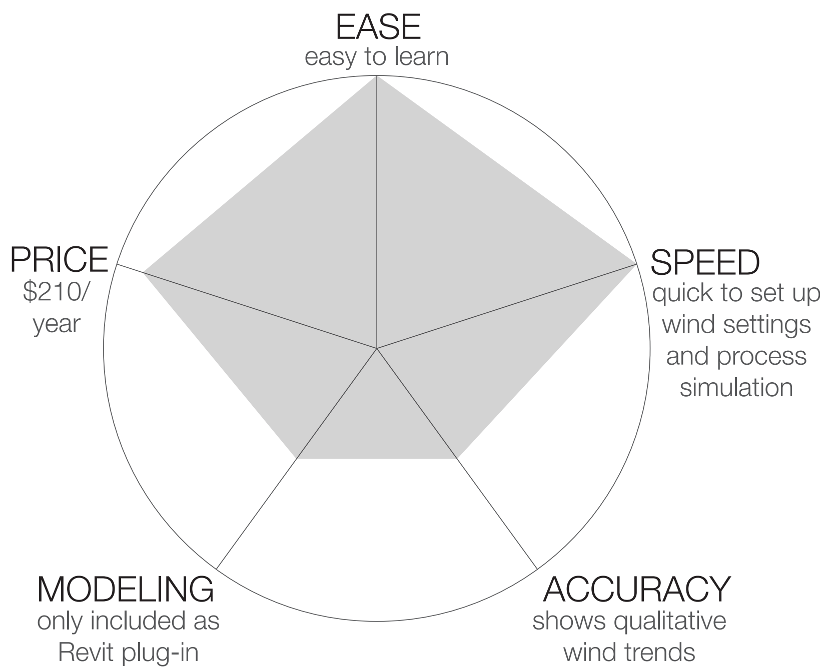


Fig. 1.55. Flow Design software ranking diagram.

FLOW DESIGN

Software Type

CFD

Made By

Autodesk

Software Compatibility

Rhino files | Revit plug-in

Intended Use

Autodesk Flow Design simulates a wind tunnel to allow users to visualize the air flow around digital 3D models.[186] The simplicity of the program's set-up and operation makes it ideal for designers who don't have the time or the need to learn a comprehensive CFD program. It simulates only major qualitative wind trends, and is intended to provide insight into wind patterns at early stages of building massing.[187] Like Vasari, the speed with which results can be obtained is useful during early project stages, but the designer should be aware that the CFD analysis is not always accurate. The program, however, is still useful in depicting general wind trends. Flow Design can run files from Rhinoceros, or can be used as a plug-in for Revit.[188]

SIMULATION CFD

Software Type

CFD

Made By

Autodesk

Software Compatibility

Revit files

Intended Use

This program provides relatively accurate fluid dynamics analysis tools.[189] It is intended for use by professionals who need to regularly perform complex CFD simulations and obtain accurate results.[190] However, it is still not as accurate as a physical wind tunnel simulation, so other programs that are more accessible to architects, even if not as accurate as Simulation CFD, are preferred for the purposes of this thesis. Also, it is recommended that users of this program attend a 2-3 day fundamentals course, as well as hire a CFD consultant for additional help with the program,[191] which would likely make architectural firms less inclined to integrate this software into their working methods. Due to the steep learning curve, as well as intensive hardware requirements and high cost,[192] this program has been deemed unrealistic to incorporate into architects' design practices and has been removed from consideration for use in this thesis.

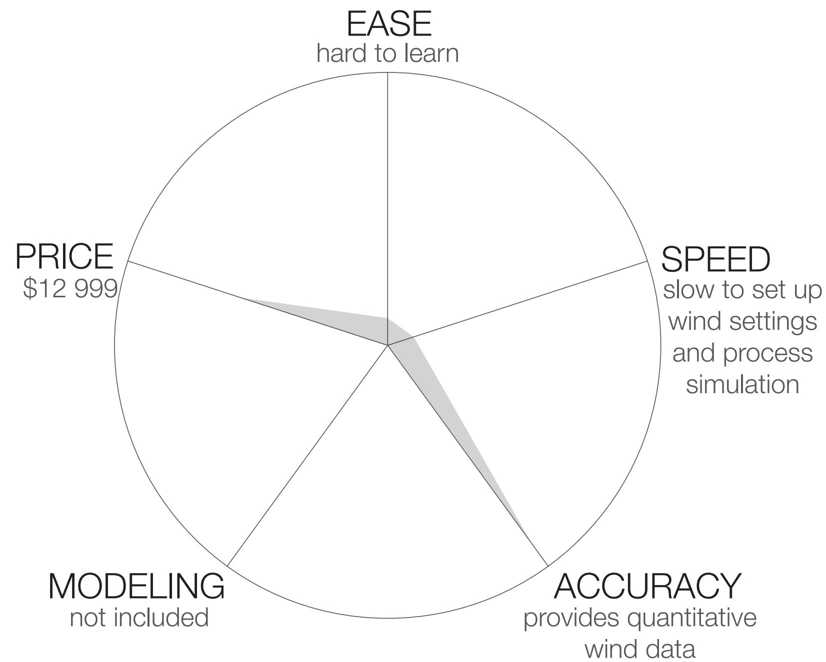


Fig. 1.56. Simulation CFD software ranking diagram.

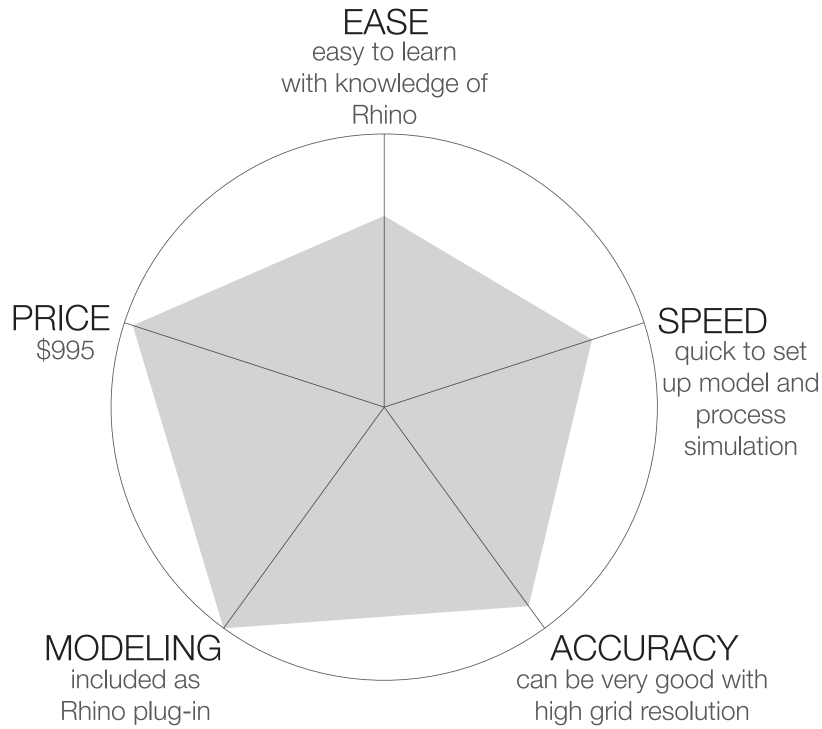


Fig. 1.57. Scan&Solve software ranking diagram.

SCAN&SOLVE

Software Type

FEA

Made By

Intact Solutions

Software Compatibility

Rhino plug-in

Intended Use

Scan&Solve is a plug-in for Rhinoceros that allows the designer to apply materials, restraints, and loads to the Rhinoceros model, and then evaluates the model's reaction to the simulated forces.[193] The program works with native Rhinoceros geometry, and unlike many other FEA programs, it does not require a separate meshed model in order to perform the analysis.[194] The analysis can be quite accurate, depending on the grid resolution that is set by the user.[195] It is intended to provide designers with finite element analysis of both conceptual and detailed models.[196]

SOFiSTiK RHINO INTERFACE

Software Type

FEA

Made By

SOFiSTiK

Software Compatibility

Rhino plug-in

Intended Use

The SOFiSTiK Rhino Interface integrates Rhinoceros into the SOFiSTiK environment.[197] It creates a mesh from a Rhinoceros model on which it then performs finite element analysis.[198] This would provide the advantage of allowing architects to use the Rhinoceros interface that they are familiar with to carry out this analysis. However, although the analysis can be carried out within Rhinoceros, all loading must be applied via text-based input, making the program too complex to be feasibly integrated into architects' design practices.[199] It is intended to be used by structural engineers,[200] so it has been removed from consideration for use in this thesis.

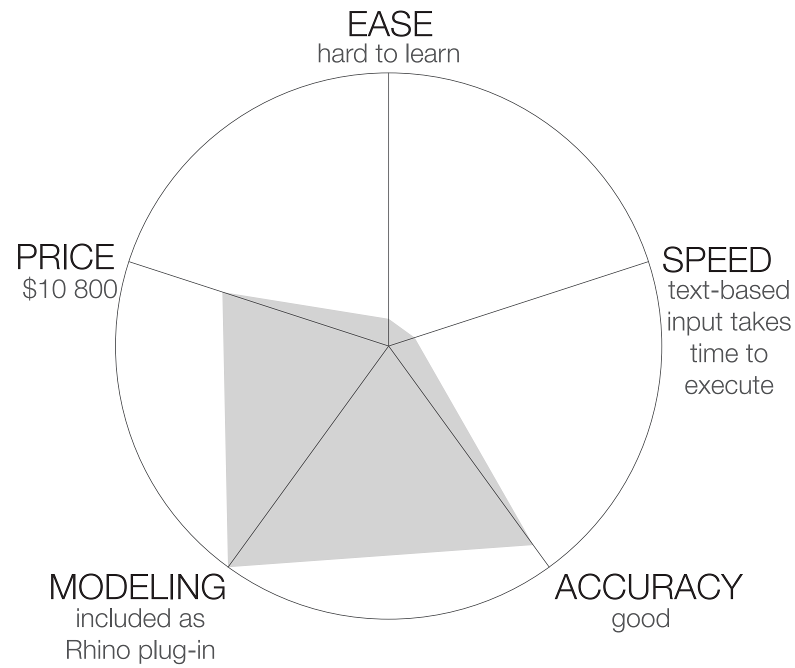


Fig. 1.58. SOFiSTiK Rhino Interface software ranking diagram.

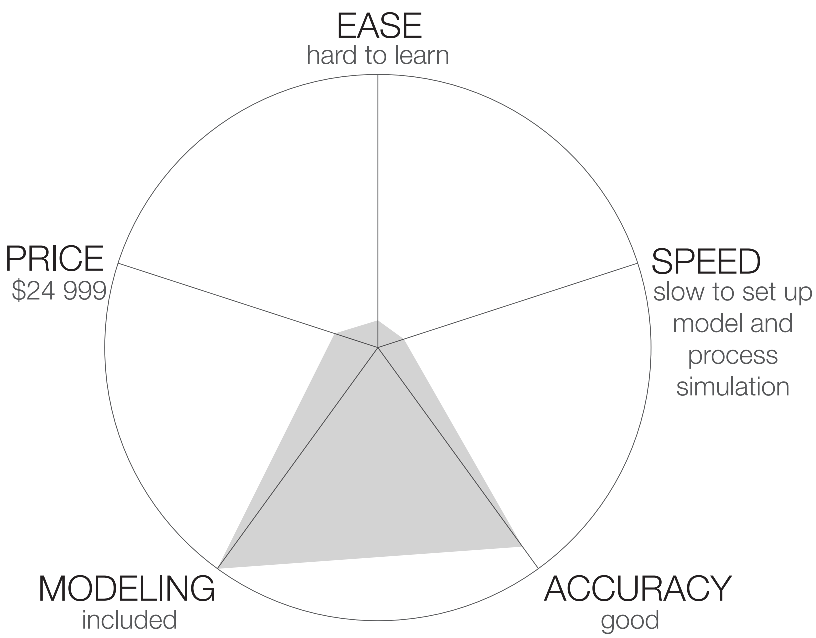


Fig. 1.59. Simulation Mechanical software ranking diagram.

SIMULATION MECHANICAL

Software Type
FEA

Made By
Autodesk

Software Compatibility
Rhino files

Intended Use
Simulation Mechanical allows designers to both model geometry and run detailed FEA simulations on that geometry within the same program.[201] Due to the steep learning curve, large hardware requirements, and high cost,[202] this program has been deemed unrealistic to incorporate into architects' design practices and has been removed from consideration for use in this thesis.

SELECTED PROGRAMS

Based on the evaluation of the five factors in relation to the considered software programs, Autodesk Vasari and Autodesk Flow Design are the selected CFD programs to be used in the design method, and Scan&Solve is the selected FEA program.

FLOW DESIGN

In this design method, Flow Design's flow line animations (Fig. 1.60) and colour gradients representing the wind pressure acting on the model surface (Fig. 1.61) are used to visualize wind turbulence and pressure on and around the building.

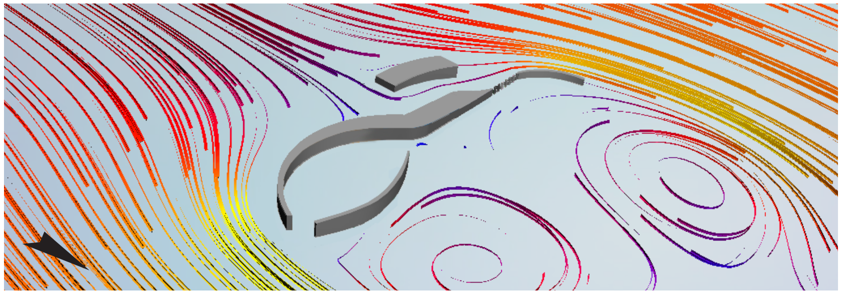


Fig. 1.60. Flow line animation from Flow Design.

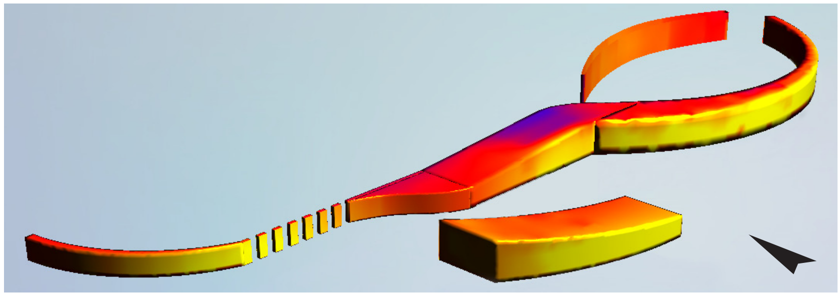


Fig. 1.61. Wind pressure colour gradient from Flow Design.

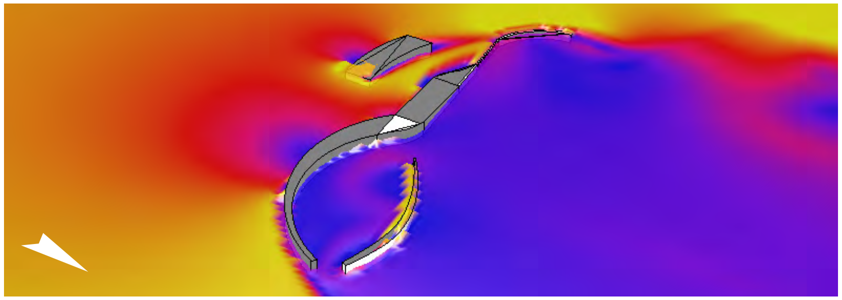


Fig. 1.62. Wind speed data slice from Vasari.

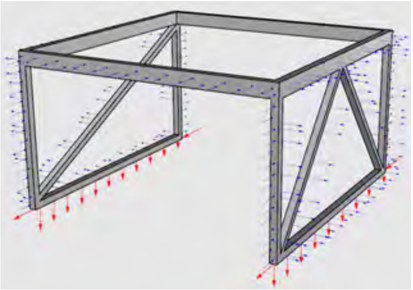


Fig. 1.63. Input loading (blue) and reactions (red) in Scan&Solve.

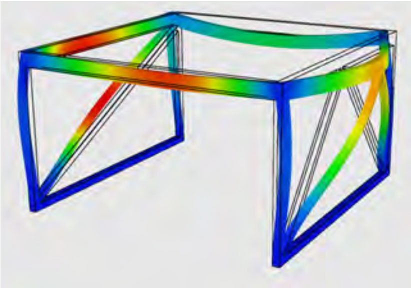


Fig. 1.64. Displacement colour gradient overlaid on deflection animation from Scan&Solve.

VASARI

Vasari's horizontal data slices depicting wind speed (Fig. 1.62) are used to evaluate the surrounding wind conditions that are created by each building form iteration.

SCAN&SOLVE

Colour gradients representing the displacement of each point of the model under load overlaid onto deflection animations of the model under load (Fig. 1.64), is the most useful output from Scan&Solve for this design method. Scan&Solve also provides visualizations of the input loading, represented by the blue arrows in Fig. 1.63, with red arrows added by the author to show the reactions to the loading.

ACCESSIBILITY OF METHOD

Most CFD and FEA software is designed for use by engineers, rather than architects. However, software is a valuable tool for architects as it allows them to integrate engineering considerations into their design methods. This may only be made possible if software is selected that could be feasibly integrated into current architectural working practices, so that architects do not have to substantially alter their current methods to be able to incorporate the use of the software. The design method that is developed in this thesis is therefore made accessible to architects by selecting software that is normally intended for engineering use, and appropriating it for the initial architectural design stages. The selected programs have the following qualities that make them appropriate for architectural purposes, and make them potentially easy to integrate within architects' current working methods:

1. EASY TO LEARN
   The selected programs are easy to learn even without previous experience with similar types of software. This will make architects more inclined to take the time to learn them, and allow them to spend less time learning the software and more time using it to test their design iterations. Within the field of engineering, it is generally good practice to use the simplest software that also fulfills the analysis requirements for which it is needed.[203] This practice is especially advantageous when engineering software is being used in the early architectural design stages, as architects have less knowledge and training than engineers that would allow them to use complex engineering software. It is therefore critical to select simple programs that can be easily learned and integrated into current architectural working practices.

2. QUICK TO RETURN RESULTS
   The programs used in this thesis can all quickly provide the user with results. This allows more design iterations to be tested and refined because the software can perform the calculations and simulations much faster than if the architect were to have to learn to do them manually. For the purpose of initial architectural design, it is more advantageous to be able to test these design iterations quickly and refine them based on general results provided by the software, instead of using a software that provides unnecessarily detailed results for this design stage and takes much longer to do so. The speed with which the results may be obtained from each of the programs also allows the architect to test enough iterations to eventually develop an intuition of what these results will be, even before the simulations are run.

3. AUTOMATE PROCESSES
   While many CFD and FEA programs require the user to manually adjust many of the settings, the chosen programs automate a lot of these processes to simplify the operation of the software and reduce the knowledge that is required from the user to

run the simulations. For example, the chosen CFD software automatically sets the grid resolution, so that the user only has to input wind speed and direction. Similarly, the complicated and time-consuming meshing process that must be done manually in many FEA programs is automated in the chosen FEA software. This means that architects do not have to spend time learning how to mesh their models. This automation of complicated processes allows architects to integrate engineering considerations into their current architectural practices, without having to acquire extensive knowledge about engineering principles and software operation.

4. PROVIDE VISUAL OUTPUT

The selected programs provide visual output, rather than only numerical output, to convey the results of the simulations. These outputs include graphics and animations that provide qualitative, rather than quantitative, wind and structural information. Visual output is easier than numerical output for architects to understand and interpret because they are more familiar with visual media. Additionally, qualitative information and general trends are more useful than exact results for informing the early design stages. The design method developed for this thesis informs architects of the visual output that is best able to provide them with the necessary information to make design revisions, so that they may focus only on the output that is relevant to their purposes.

5. REQUIRE TYPICAL HARDWARE

None of the chosen programs have intense hardware requirements, and can even be run on a laptop if necessary. This means that architectural firms wanting to integrate these programs into their working practices will be able to do so with their current computers.

6. COMPATIBLE WITH ARCHITECTURAL 3D-MODELING SOFTWARE

All of the programs used in this method are compatible with 3D-modeling programs that are already commonly used by architects. This allows architects to use their current 3D-modeling software to design the building, and then test the digital model with the CFD and FEA software. This eliminates the need for architects to learn new 3D-modeling software that is compatible with the CFD and FEA software.

7. FREE EDUCATIONAL LICENSES AVAILABLE

All of the programs provide free educational licenses, so that students may learn these programs while in school to be able to use them when they enter the workforce. This would allow architectural firms to hire employees who already know how to use these programs, to be able to integrate them into their current design methods.

SOFTWARE SEQUENCE

The three programs that have been selected for use in this design method are all compatible with each other, as files from each of the programs can either be opened in, or exported to, any of the other programs. This is necessary because many of the steps in the design method need to be repeated as the building model is refined and re-tested, requiring the digital model to be opened and edited in all three programs throughout the design process. This sequence is shown in Fig. 1.65, along with the file formats and conversion processes that should be used to maintain compatibility among the programs.

1. For each building design iteration, Vasari is first used to model the building form.

2. Vasari is then used to simulate the speed of the wind flow around the Vasari model. This tests the wind conditions that will be created around the building. The model may be adjusted within Vasari and re-tested in the simulated wind conditions as necessary.

3. The building model is then exported to Flow Design, which is used to evaluate the turbulence around the building model with flow line animations. The architect can change the building form in Vasari to reduce the wind turbulence as necessary, and then re-export and re-test the model in Flow Design to ensure that the surrounding wind patterns are altered desirably by the adjusted building form.

4. The building model is then exported from Vasari and tested in Flow Design to evaluate the aerodynamics of the building form. This may be done with the information provided by Flow Design about the wind pressure that is exerted on each building face. The architect can change the building form in Vasari to reduce the wind pressure acting on it, and then re-export and re-test the model in Flow Design to ensure that improved aerodynamics have been achieved without compromising the surrounding wind conditions.

5. Next, the Vasari model is exported to Rhino, in which a structural bay is modeled that will be repeated throughout the building form.

6. Finite element analysis is then run on the Rhino model of the structural bay, as the wind pressure information that is provided by Flow Design is input into Scan&Solve to predict how the bay will react to combined wind and gravity loading. The model of the bay may be adjusted as needed within Rhino, and then the finite element analysis may be re-run on the adjusted model until it is structurally adequate.

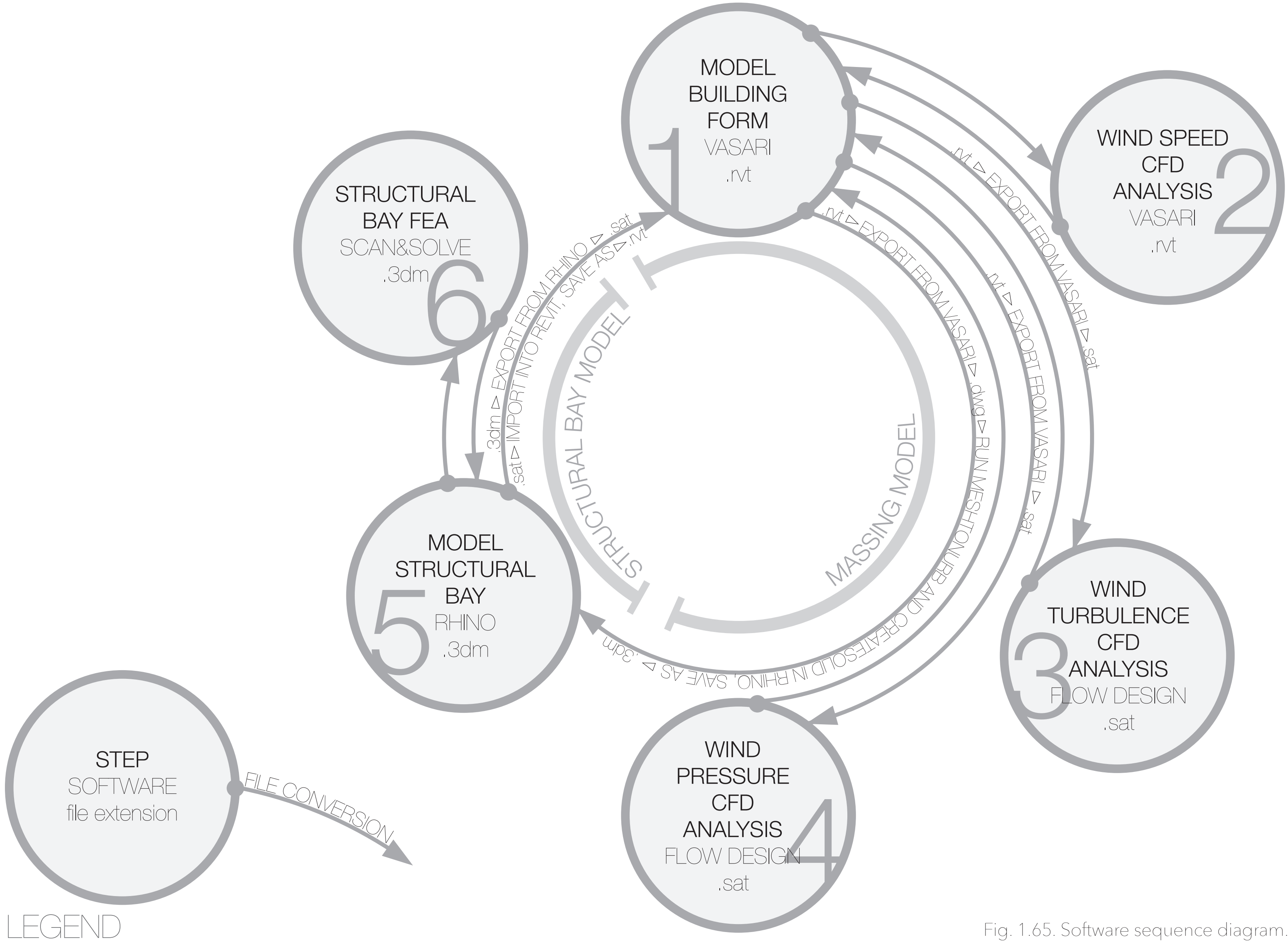


Fig. 1.65. Software sequence diagram.

PROGRAM AND SITE

PROGRAM AND SITE CONDITIONS

The thesis does not serve to propose a specific building. Instead, it uses the design of a small, low-rise building as a means of developing the proposed design method that may be applied to a multitude of building, program and site requirements. As such, the exterior programs are not a program proposal, but a means of providing a variety of wind conditions to be created with the building form. Similarly, the building form does not reflect interior program placement or size requirements, but is instead a form that responds primarily to the creation and resistance of wind conditions. The site was chosen to provide an extreme context within which to develop the design method.

Once the wind and spatial conditions are defined with the chosen program and site, the design method is developed within these specified conditions, using a single building on a simple site to provide a basis for potentially more complex contexts.

PROGRAM

The exterior program activities (Fig. 2.1) serve to provide a variety of wind condition requirements to be created with the building form, and are not a program proposal in themselves. These programs consist of pairings of wind energy generation technologies and seasonal sports that require specific wind conditions. To support the exterior programs, the building itself could accommodate energy storage, space to record and compare energy generation data from the wind energy generation technologies to be tested on the site, as well as equipment storage and change room facilities to support the sports programs. The building form does not reflect interior building design, program sizes or program placement requirements, but is instead a form that creates the wind conditions that are required for the exterior programs.

These exterior programs have been diagrammed and sorted according to the area that they each require (Fig. 2.2). This diagram serves as a tool to develop different combinations of programs for different design iterations, as it conveys which programs have similar wind and spatial requirements, and which can occur within the same physical space in alternating seasons. Drawings have also been made that document the detailed wind and spatial requirements for each of the exterior programs (Fig. 2.3-Fig. 2.12). These drawings may be referred to by the architect when developing building forms to create these required exterior spaces and wind conditions.

FAST WIND

- HORIZONTAL AXIS WIND TURBINE
- COMPACT WIND ACCELERATION TURBINE
- KITE FLYING
- SNOWKITING
- SNOW WINDSURFING

SLOW WIND

- BLADE TIP POWER SYSTEM
- FIELD SPORTS
- SNOW BUILD-UP FOR SLEDDING

MINIMAL WIND

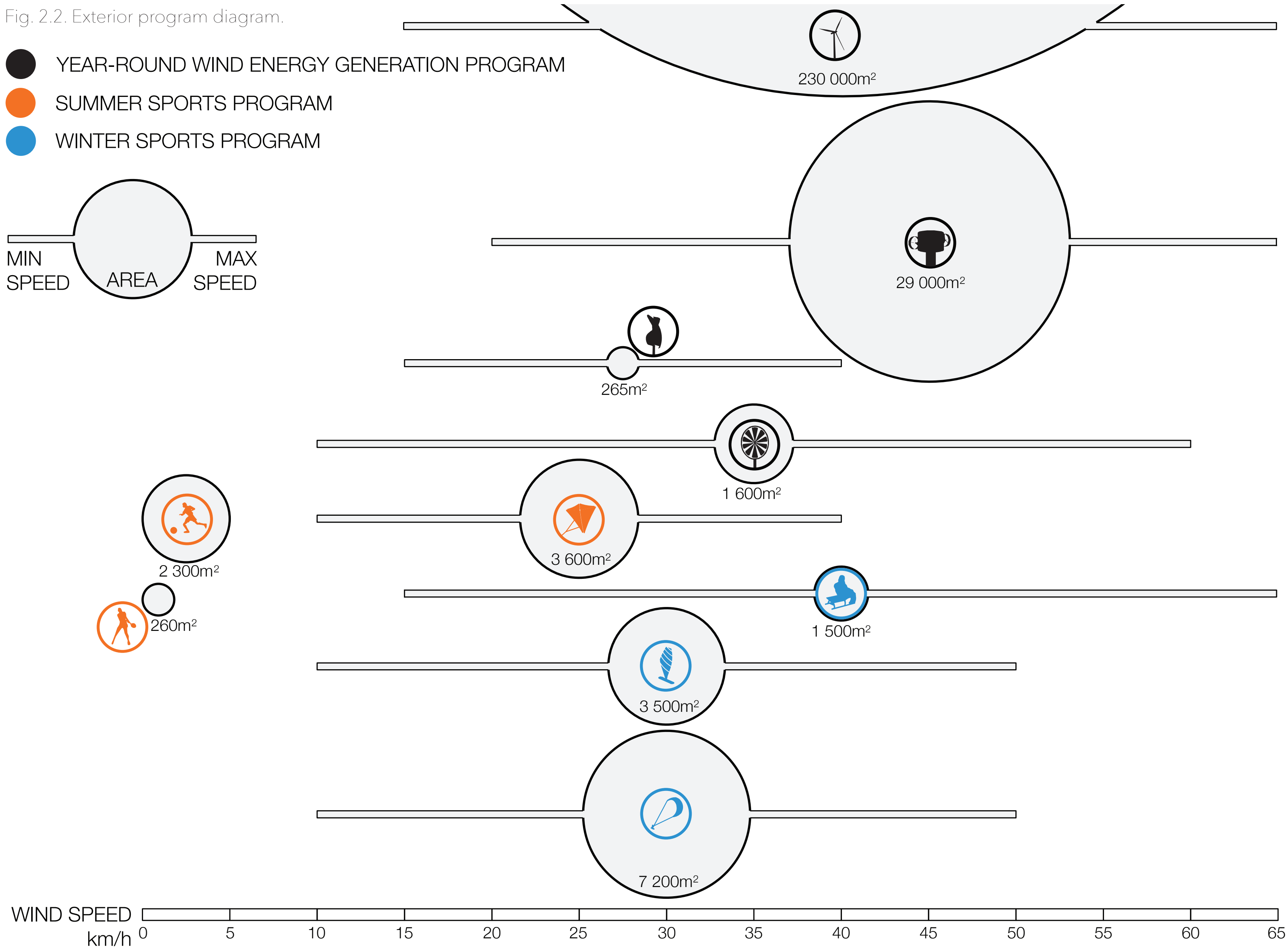
- TENNIS AND BADMINTON

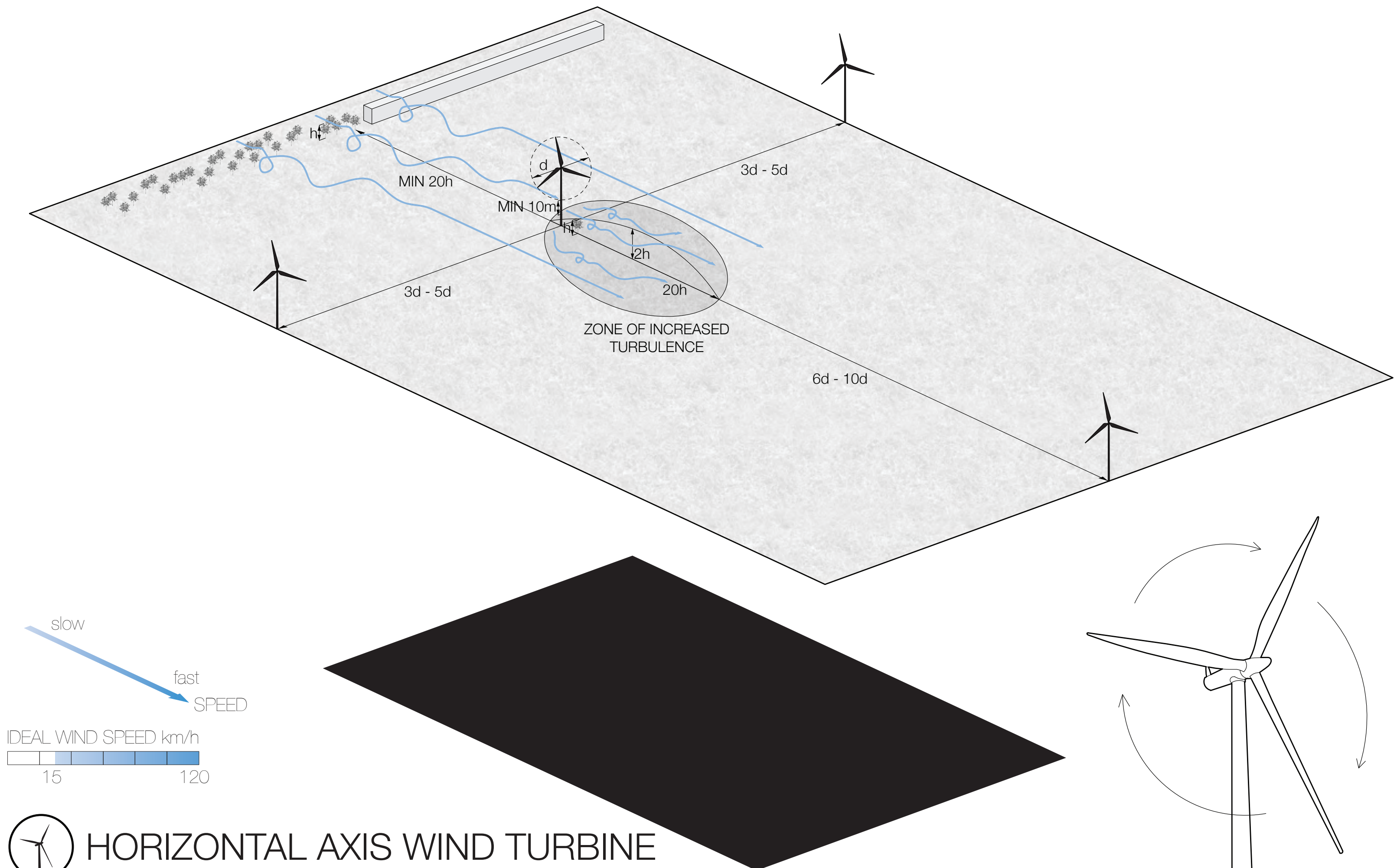
TURBULENT WIND

- VERTICAL AXIS WIND TURBINE

Fig. 2.1. Exterior program list.

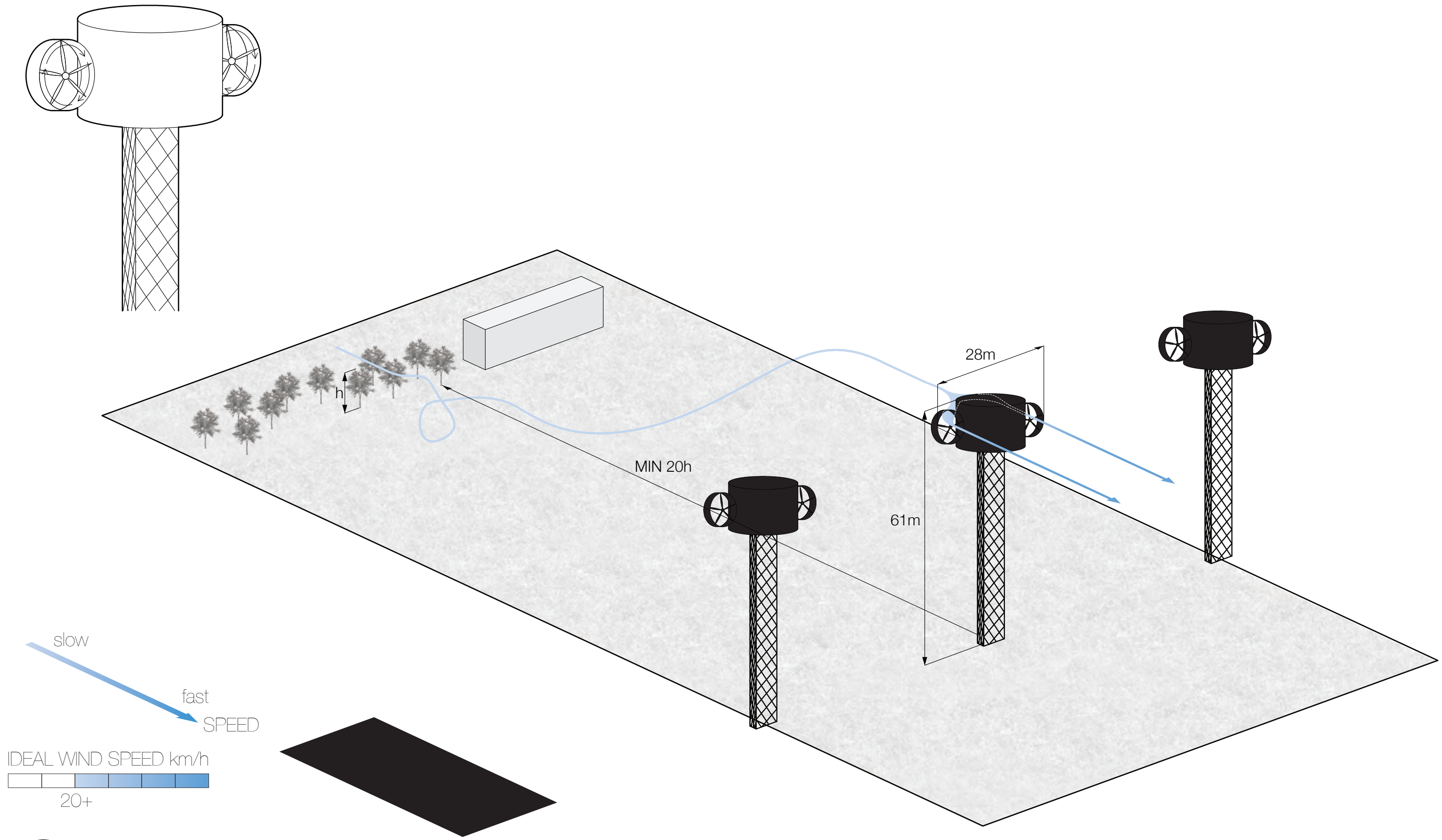
Fig. 2.2. Exterior program diagram.





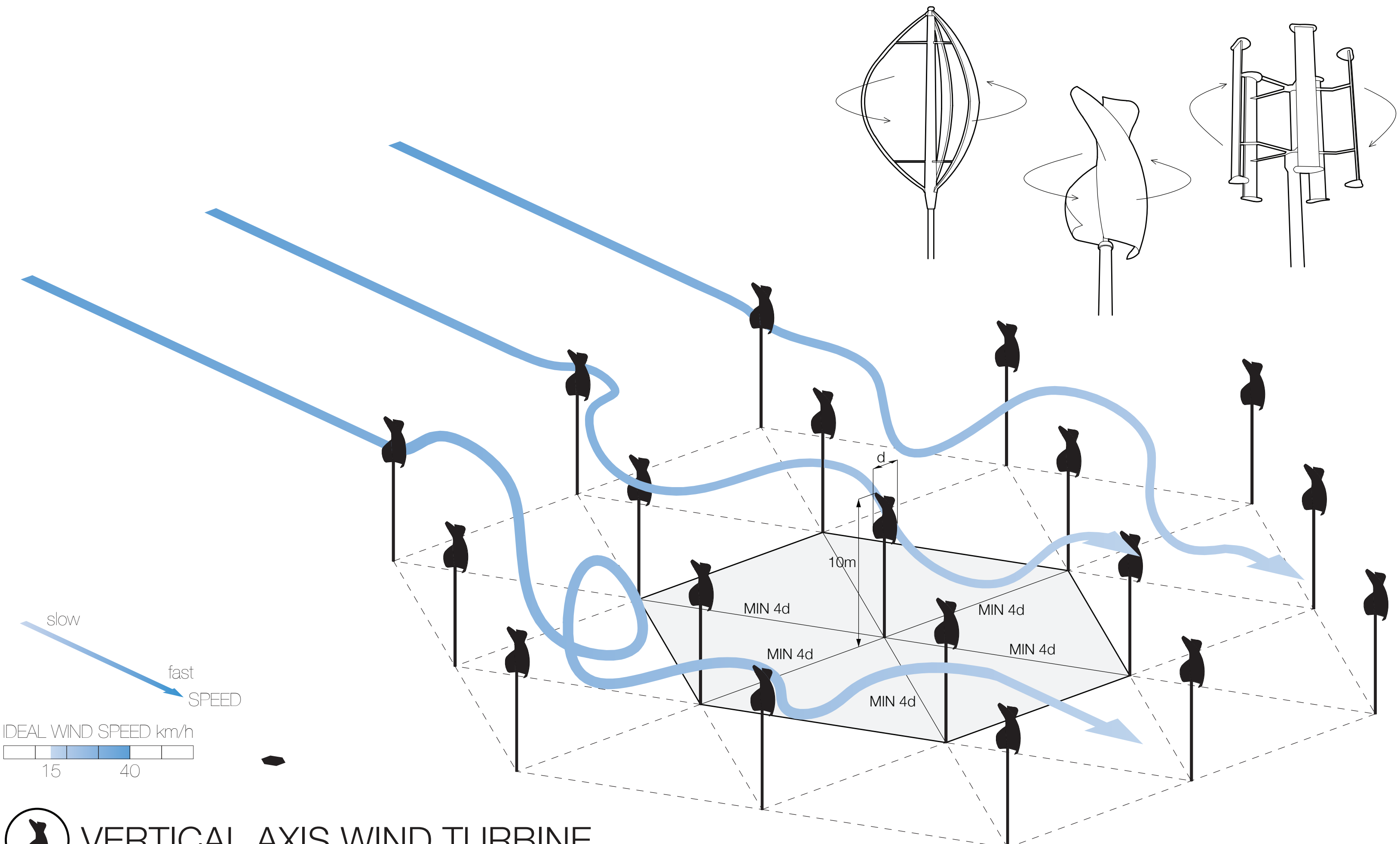
HORIZONTAL AXIS WIND TURBINE

Fig. 2.3. Horizontal axis wind turbine wind and spatial requirements.



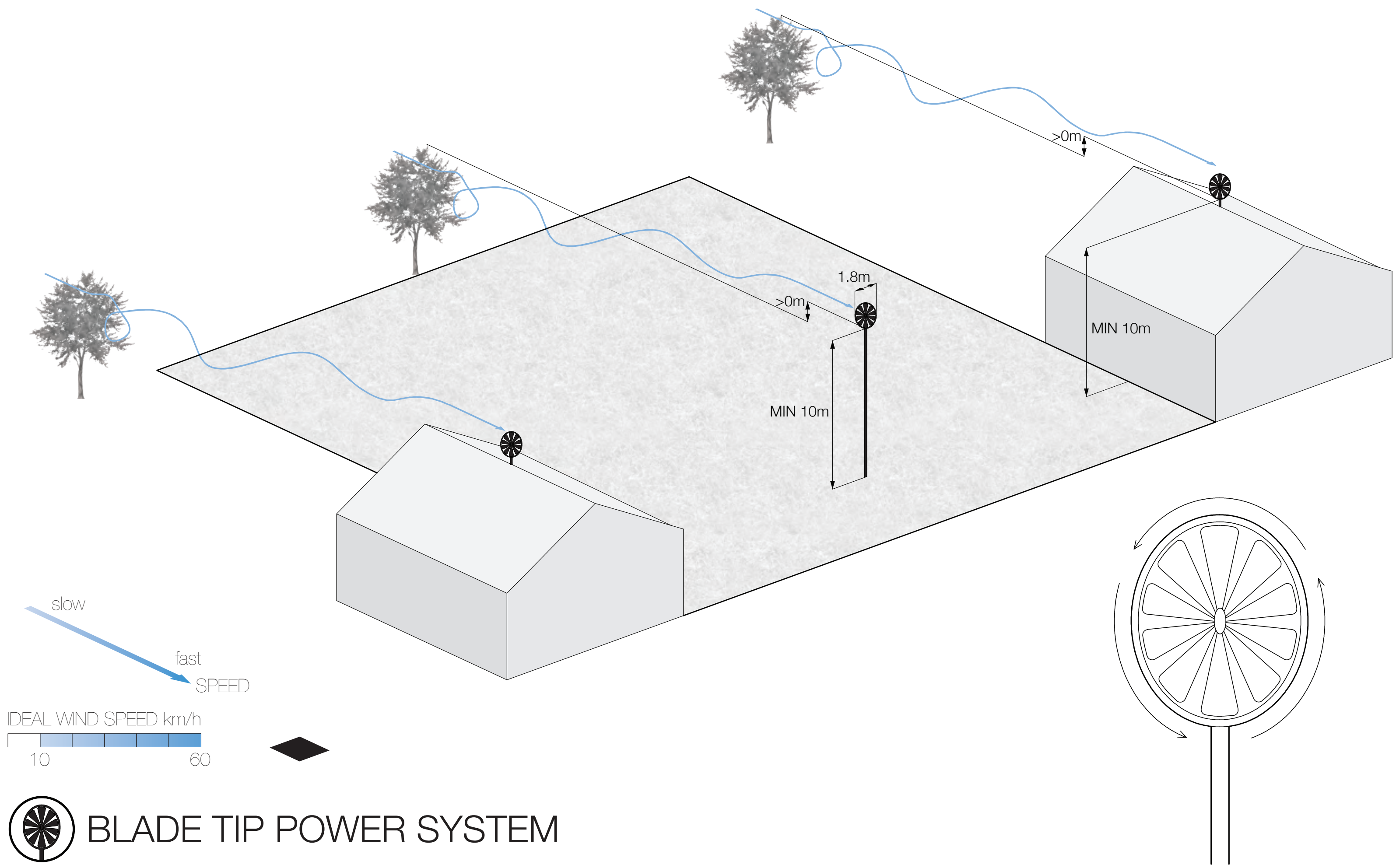
COMPACT WIND ACCELERATION TURBINE

Fig. 2.4. Compact wind acceleration turbine wind and spatial requirements.



VERTICAL AXIS WIND TURBINE

Fig. 2.5. Vertical axis wind turbine wind and spatial requirements.



BLADE TIP POWER SYSTEM

Fig. 2.6. Blade tip power system wind and spatial requirements.

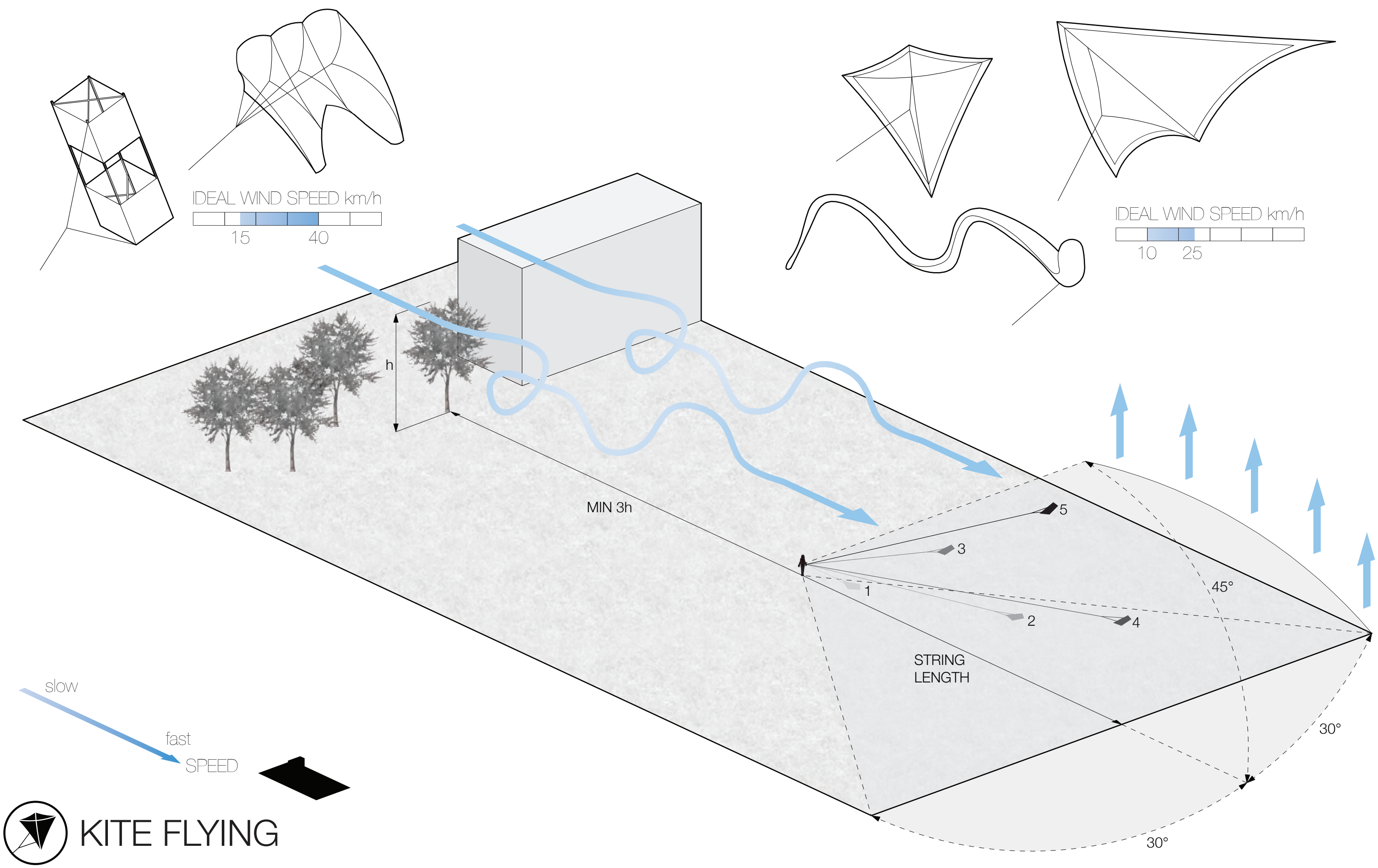
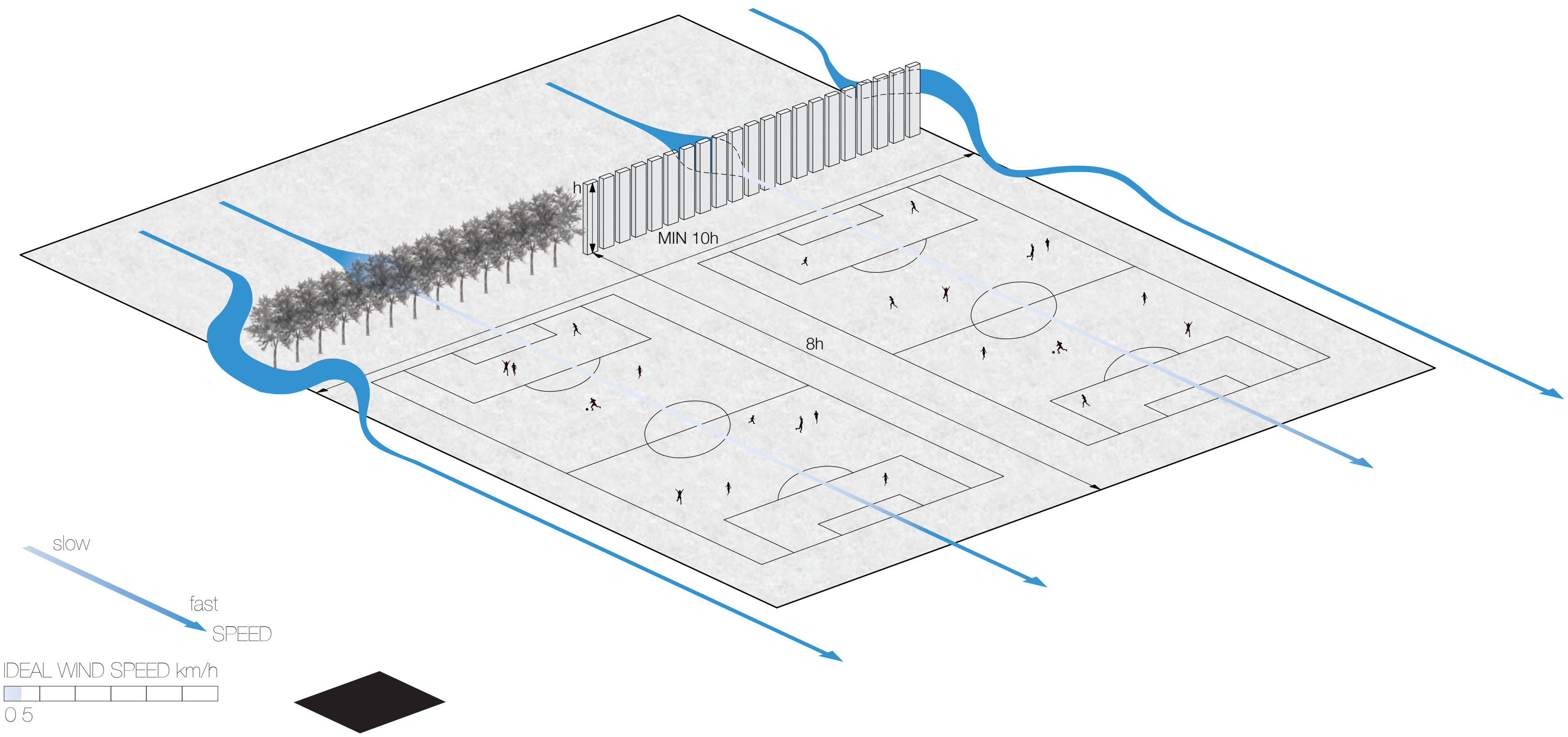
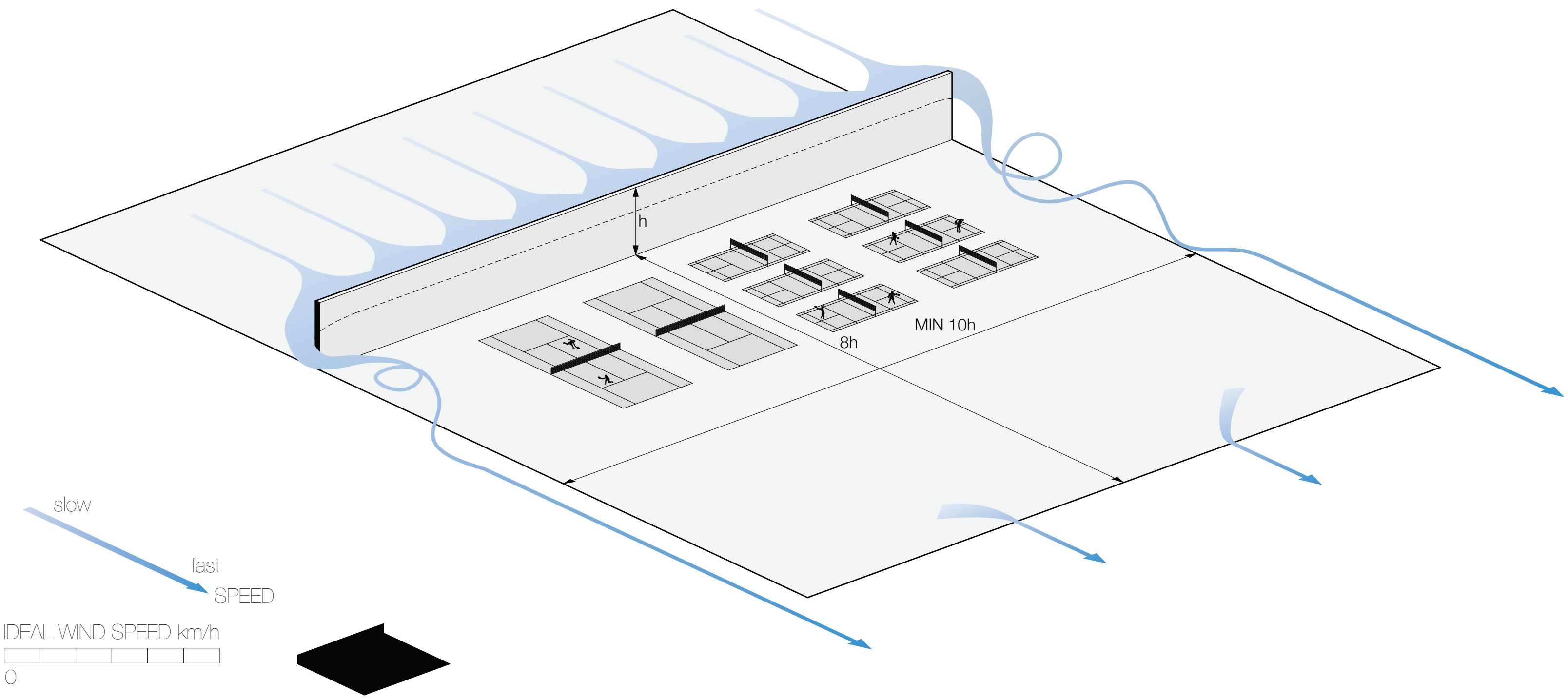


Fig. 2.7. Kite flying wind and spatial requirements.



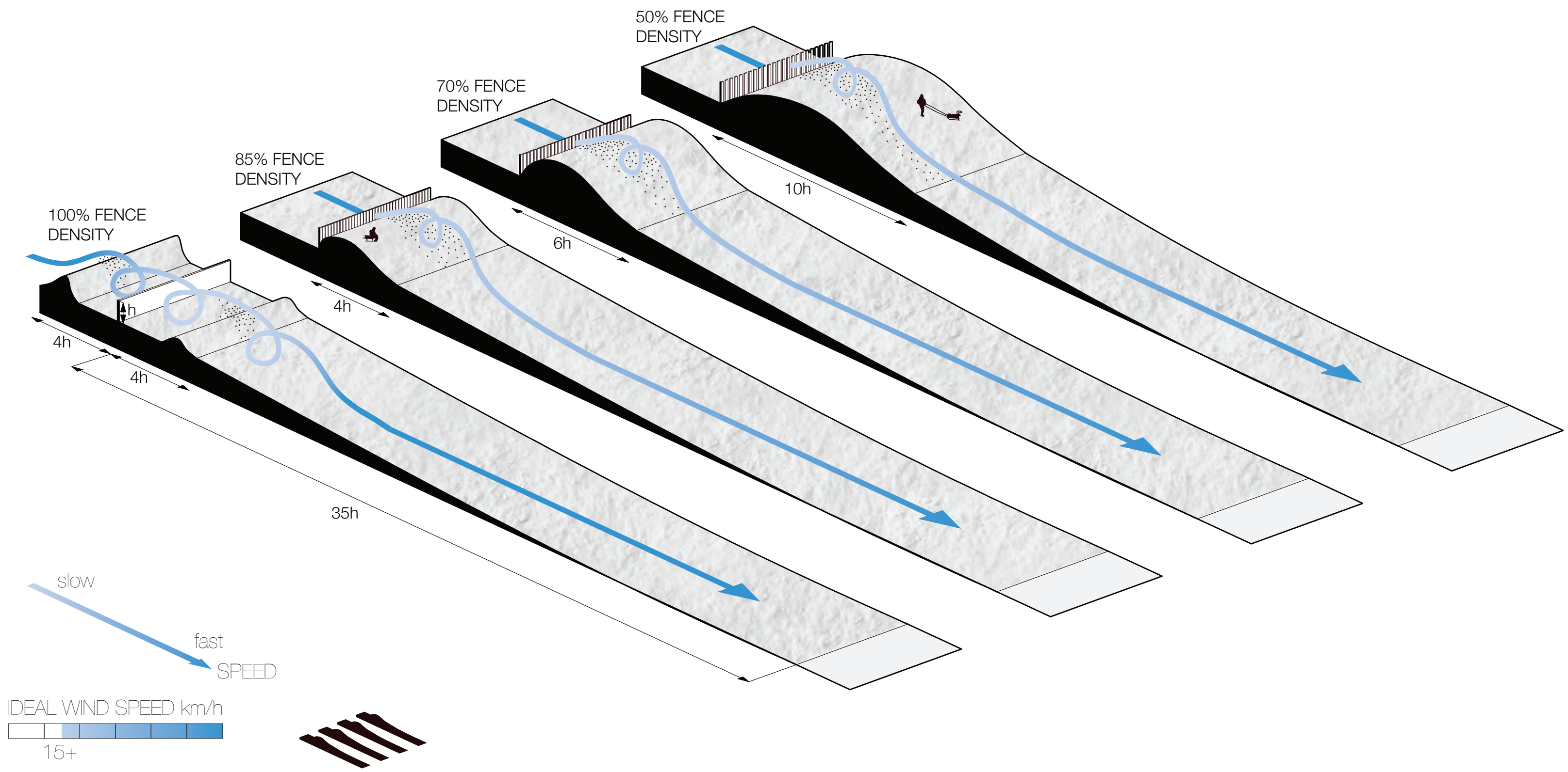
FIELD SPORTS

Fig. 2.8. Field sports wind and spatial requirements.



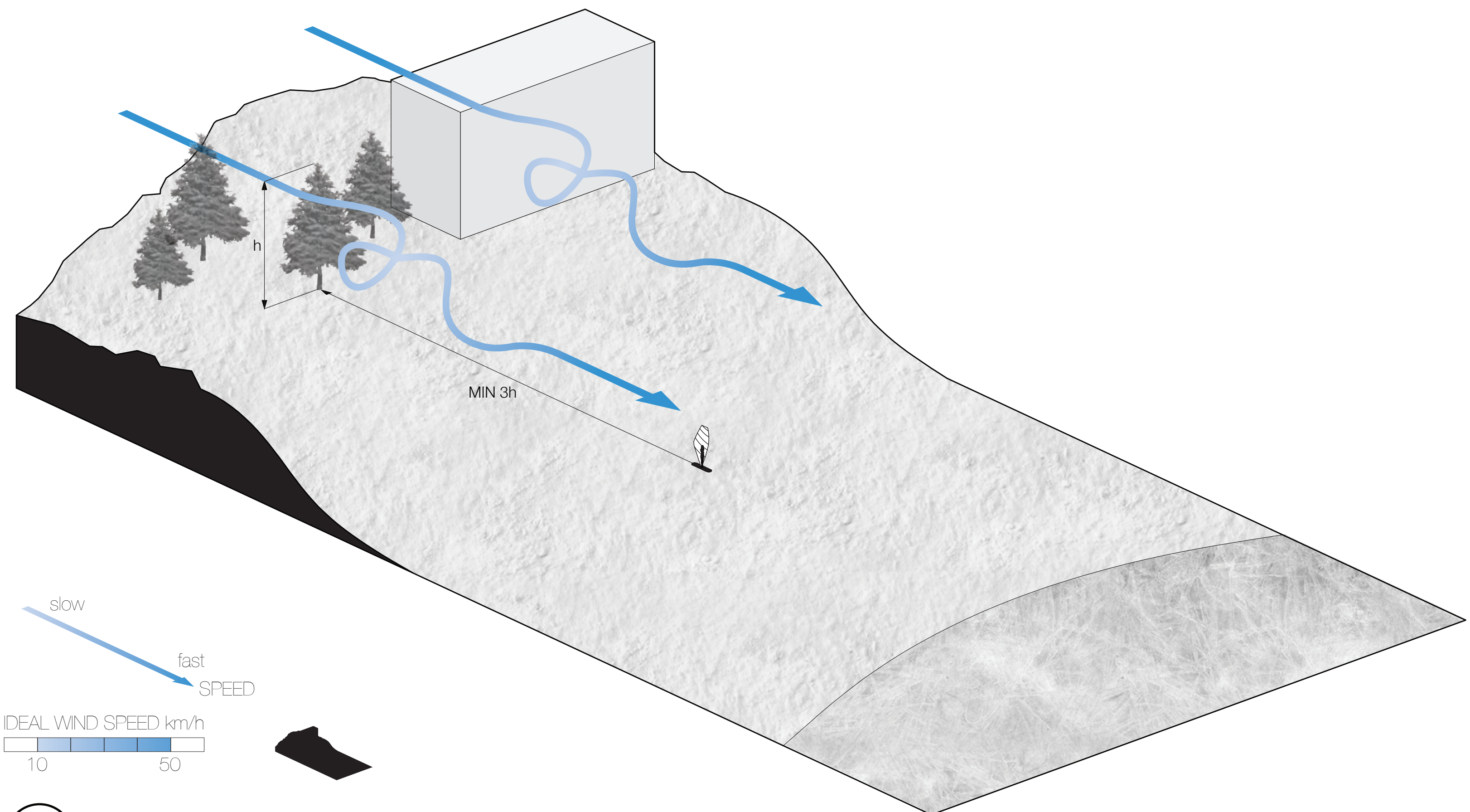
TENNIS AND BADMINTON

Fig. 2.9. Tennis and badminton wind and spatial requirements.



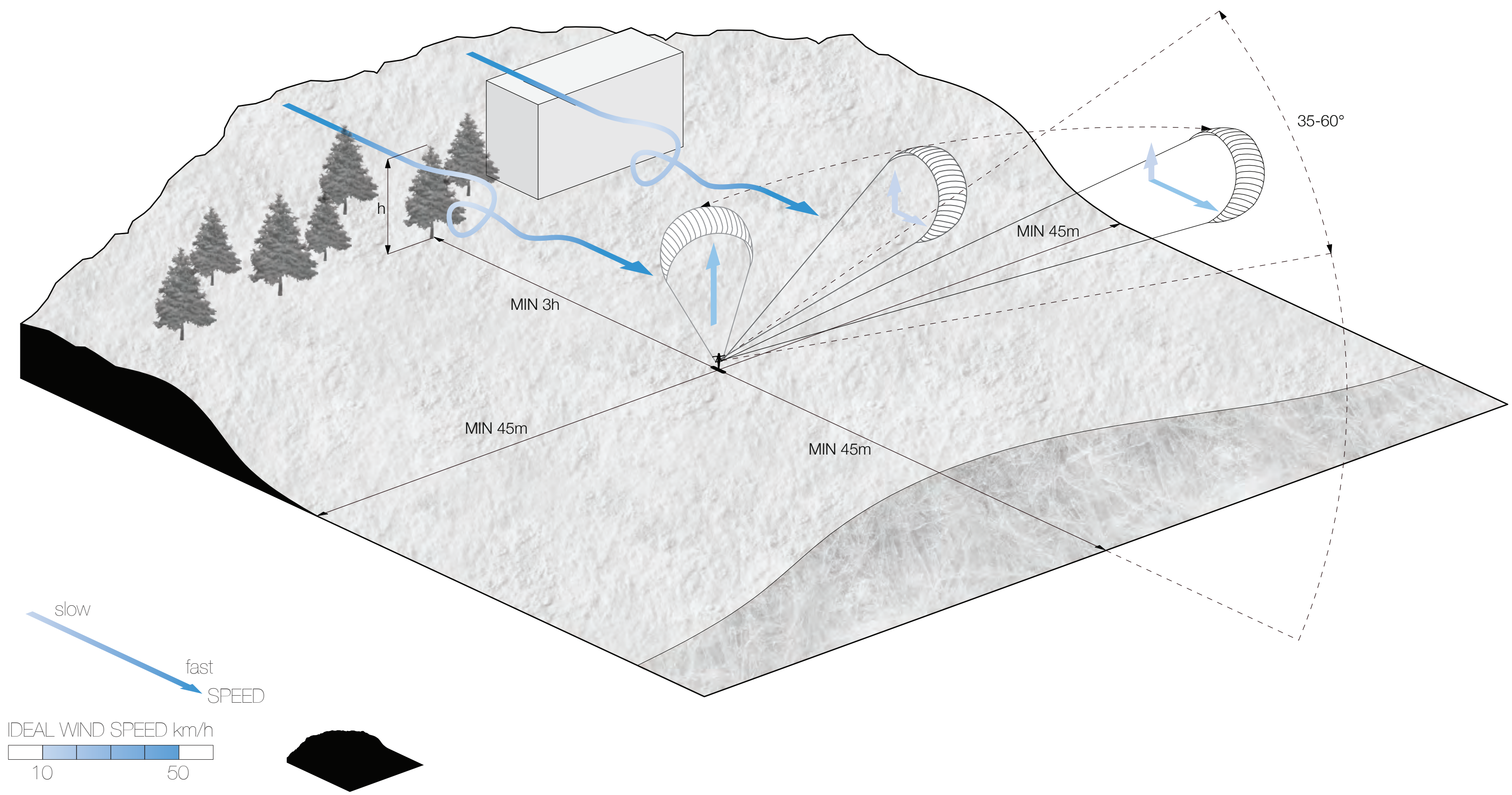
SNOW BUILD-UP FOR SLEDDING

Fig. 2.10. Snow build-up for sledding wind and spatial requirements.



SNOW WINDSURFING

Fig. 2.11. Snow windsurfing wind and spatial requirements.



SNOWKITING

Fig. 2.12. Snowkiting wind and spatial requirements.

SITE

The site on which the design method has been developed (Fig. 2.17) is an open field on the outskirts of southern Regina.

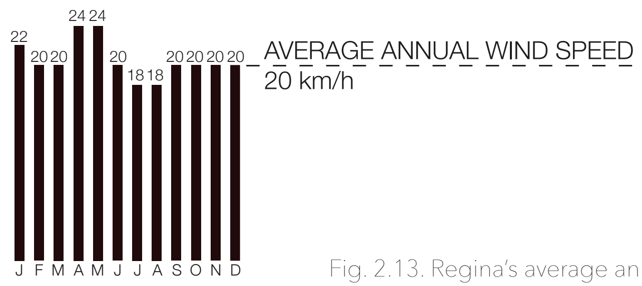


Fig. 2.13. Regina's average annual wind speed.

Regina is the fifth windiest city in Canada, with an average annual wind speed of 20 km/h (Fig. 2.13).[1] These high wind loads provide an extreme context within which to develop the design method.

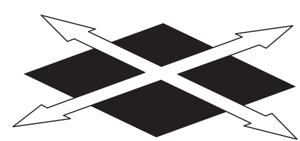


Fig. 2.14. A flat, open site was chosen.

The flat, open site (Fig. 2.14) provides an opportunity to manipulate the wind with only the building form, as there are minimal site conditions to alter the wind immediately around the building. The large site is adjacent to a residential neighbourhood so the public can easily access the exterior sports programs.

Fig. 2.15. Regina's population.

Of the top five windiest cities, it has the largest population for use of the exterior programs (Fig. 2.15).[2]

University of Regina

Fig. 2.16. The site is near the University of Regina.

The site is located near the University of Regina (Fig. 2.16), whose existing wind turbine studies[3] could potentially pair with the wind energy generation technologies that surround the building.

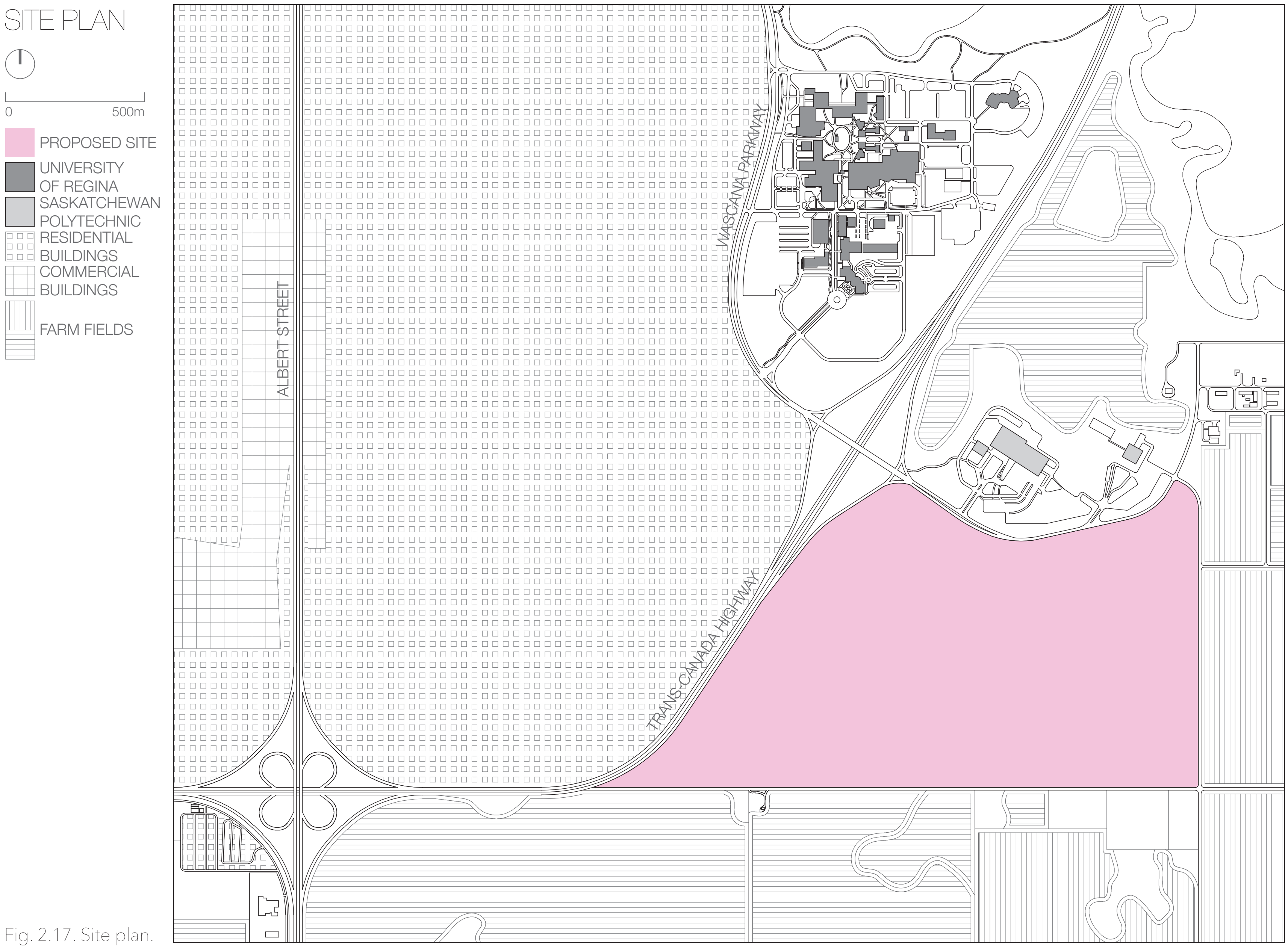


Fig. 2.17. Site plan.

ANNUAL WIND ROSE

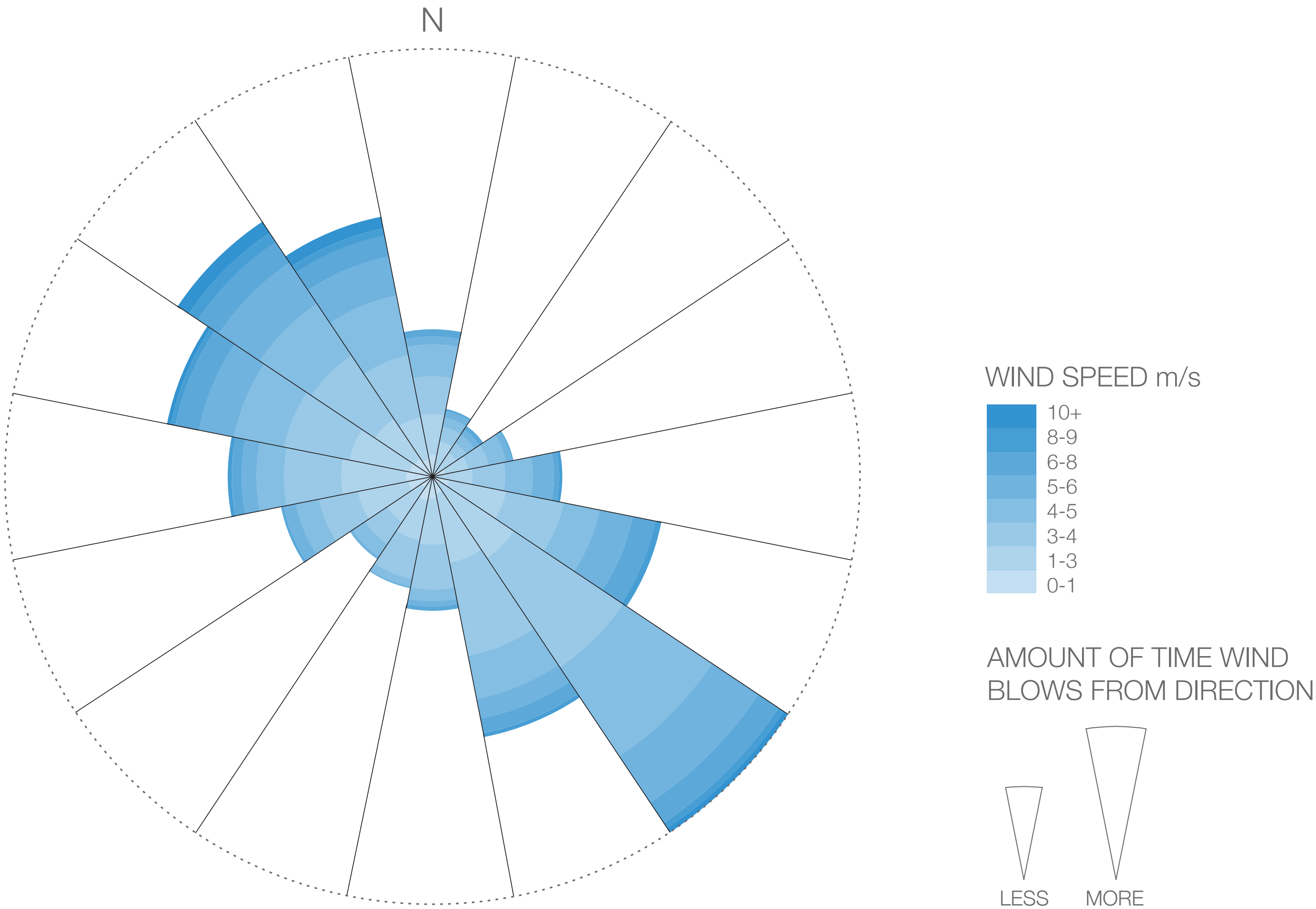


Fig. 2.18. Annual wind rose for the chosen site.

MONTHLY WIND ROSES

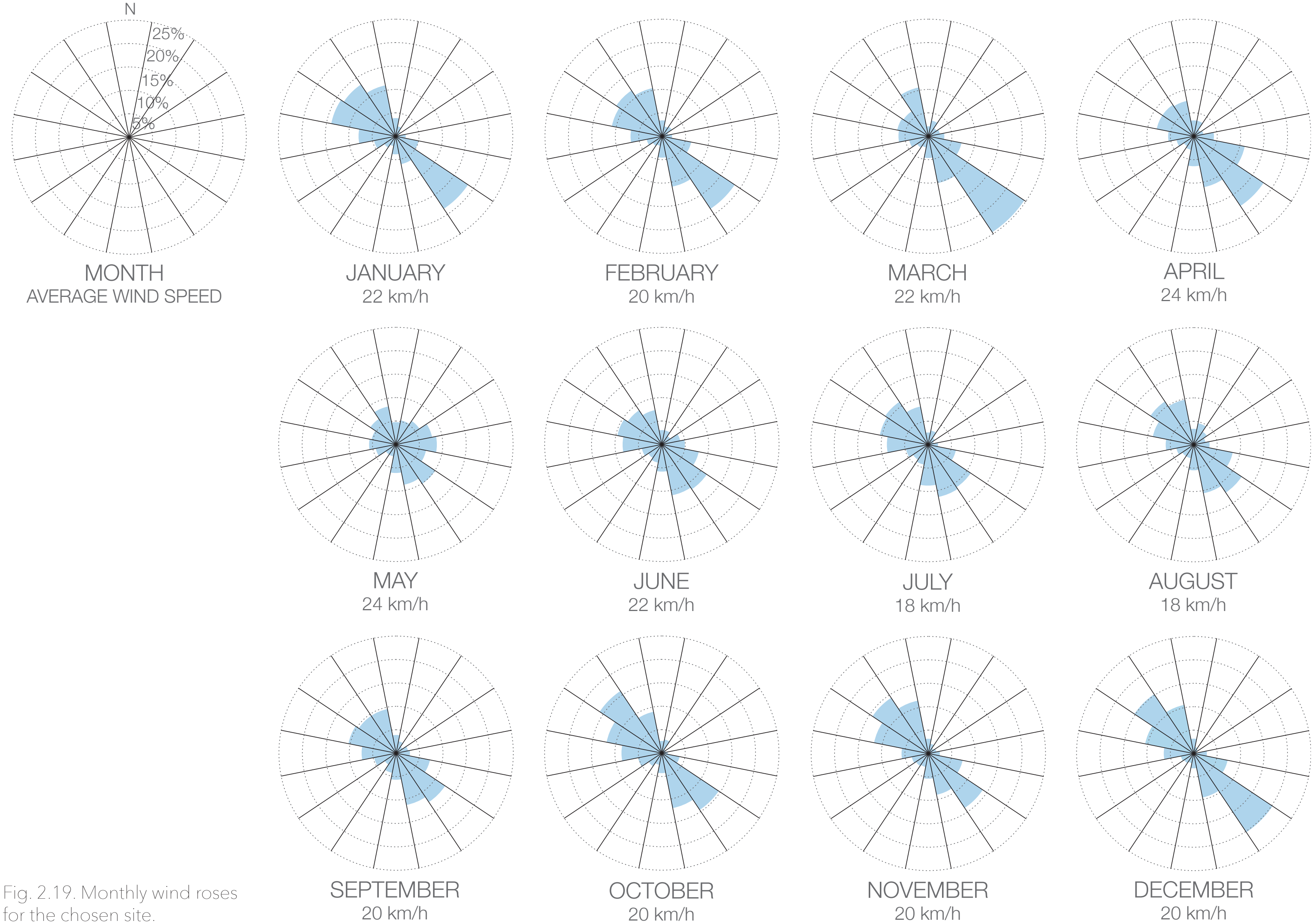


Fig. 2.19. Monthly wind roses for the chosen site.

FORM AFFECTS WIND

HOW FORM AFFECTS WIND

As air flows over surfaces with a lot of variation, it is altered more than when it flows over smooth surfaces.[1] Forms that prevent a surface from being smooth get in the way of the wind and complicate its flow by speeding it up, slowing it down, or creating turbulence.[2] Such surface features include buildings.

The first step in the design method is to design a building so that its form interacts with the wind to alter its speed and flow patterns. This manipulation of the wind should be done to create wind conditions around the building that are appropriate for the exterior programs. For each building design iteration, CFD software is used to simulate the speeds and patterns of wind flow around the initial building form design. The speed with which these simulation results are provided allows the architect to refine and re-test many iterations of their design until the building form creates the desired wind conditions.

WIND EFFECTS LIBRARY

Manipulations of building form to increase and decrease wind speed, turbulence, and pressure were studied from a broad range of published sources[3] and compiled into a library of wind effects. For each technique, a wind effect that has been studied in real wind environments is compared with the results of the simulation of the effect in both Vasari and Flow Design. Architects may refer to this library of effects to alter the building geometry in order to create the specific wind conditions that are required for the exterior programs. The software simulations of each of the effects allow the architect to become familiar with what each of the CFD programs can accurately represent, and what they don't consider when computing results. For example, neither Vasari nor Flow Design is able to depict the downwash effect, as the programs assume a uniform wind speed and do not consider the higher wind speeds that exist in reality at higher elevations. It was also learned through these simulations that Vasari's horizontal data slices are more detailed than those from Flow Design, but Flow Design's flow line animations and colour gradients representing the wind pressure acting over the model surface are more accurate than those from Vasari. While CFD software can be a useful tool for quick tests of design iterations, the architect has to know how to interpret the results and be able to tell if they are an accurate representation of the simulated effects, by possessing some knowledge of studied wind effects.

BREEZEWAY EFFECT
INCREASE WIND SPEED

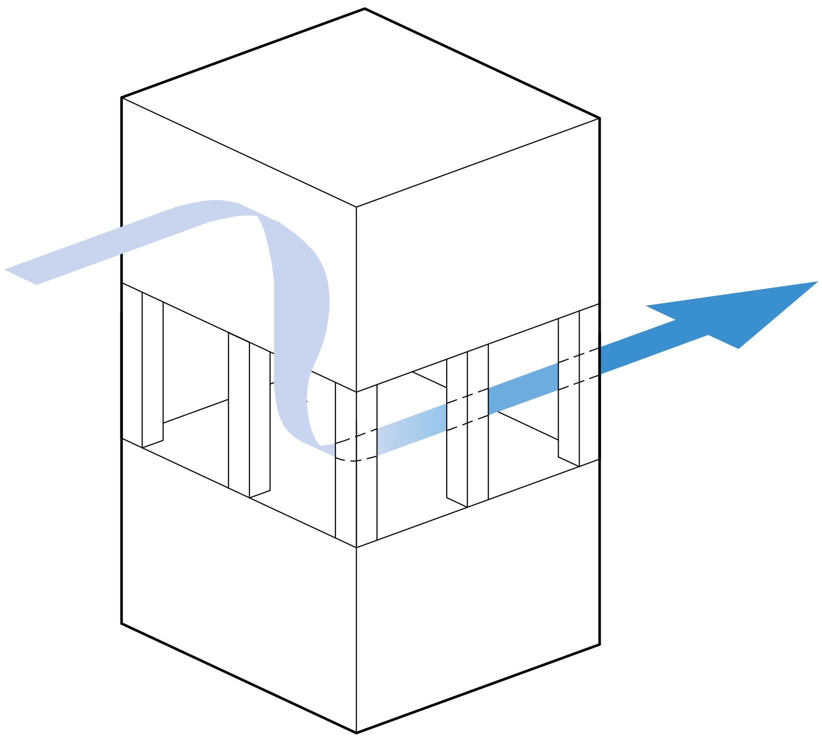
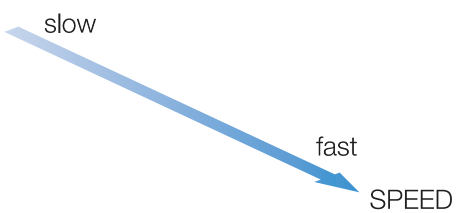
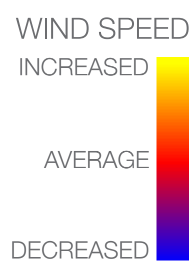


Fig. 3.1. Breezeway effect.





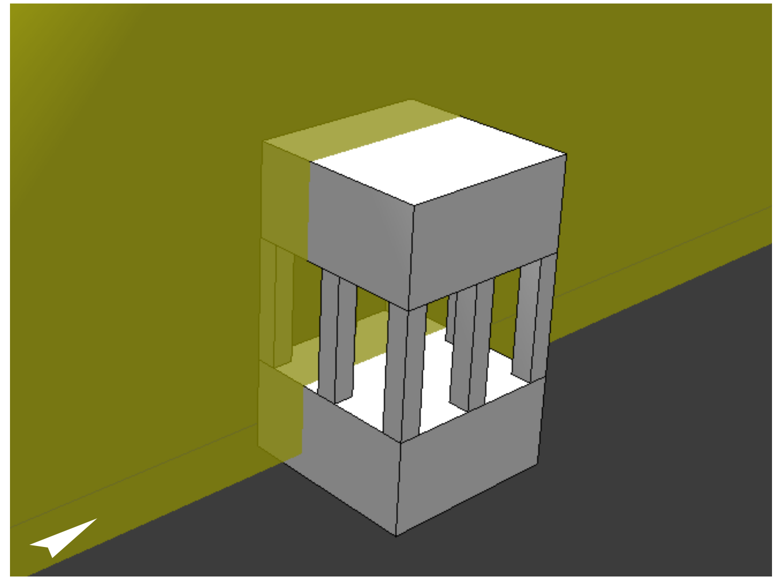


Fig. 3.2. Vasari simulation - effect not shown.

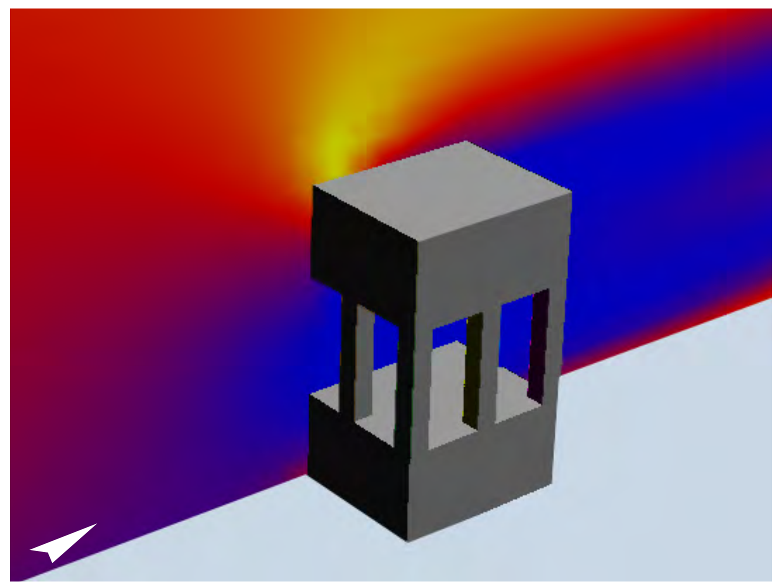


Fig. 3.3. Flow Design simulation - effect not shown.

CHANNEL EFFECT
INCREASE WIND SPEED

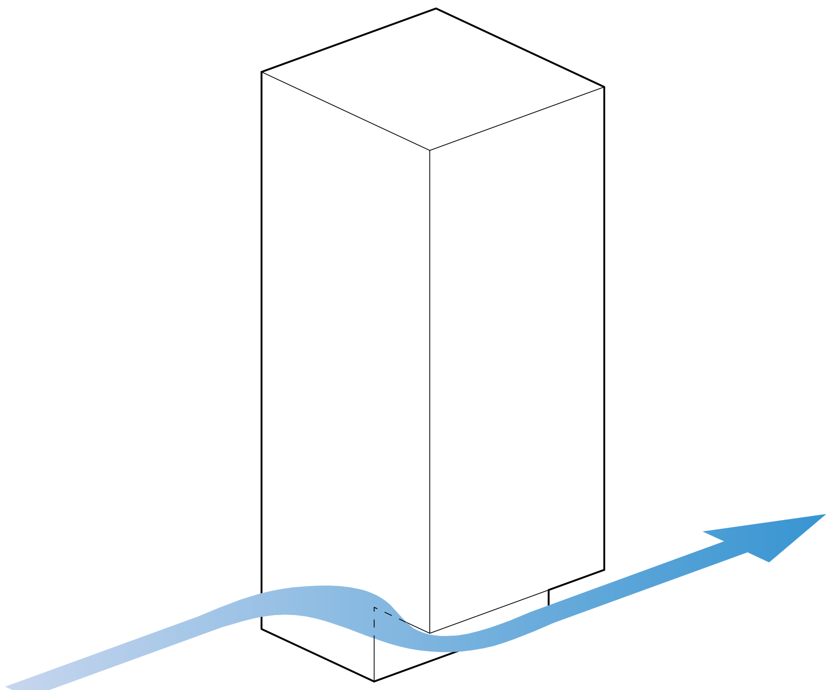


Fig. 3.4. Channel effect.

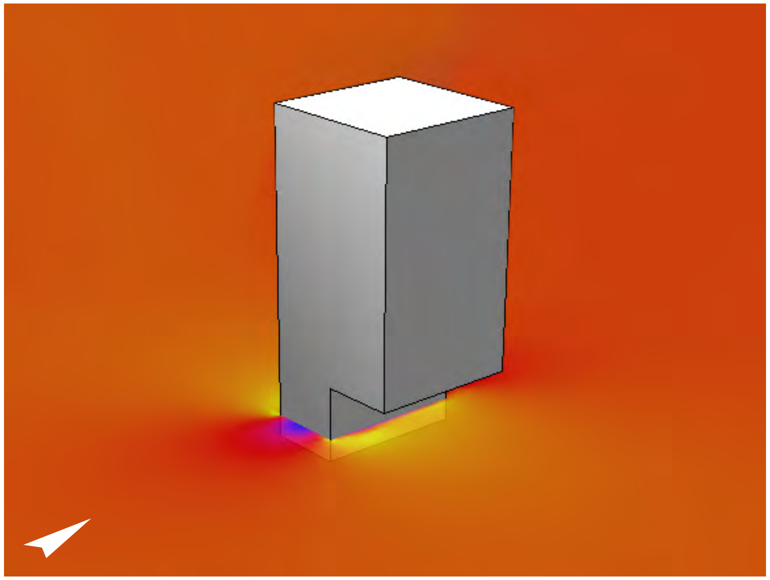
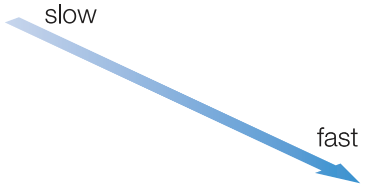


Fig. 3.5. Vasari simulation.



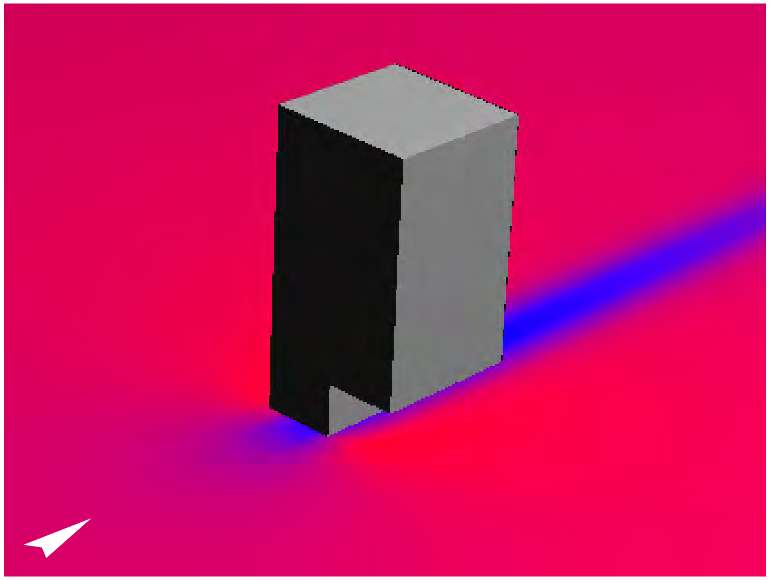


Fig. 3.6. Flow Design simulation - effect not shown.

CHANNELLING EFFECT
INCREASE WIND SPEED

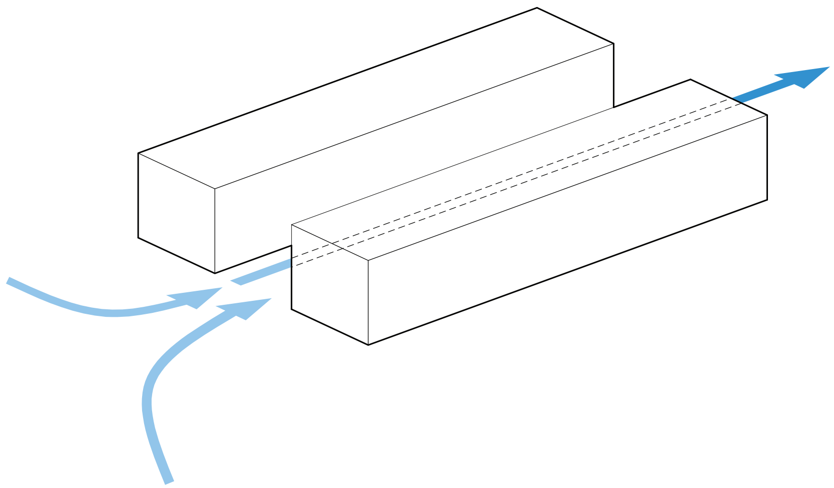
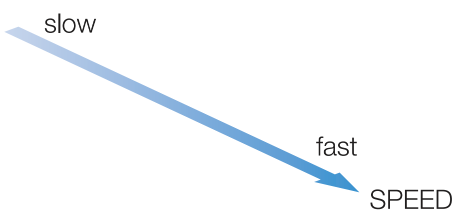


Fig. 3.7. Channelling effect.



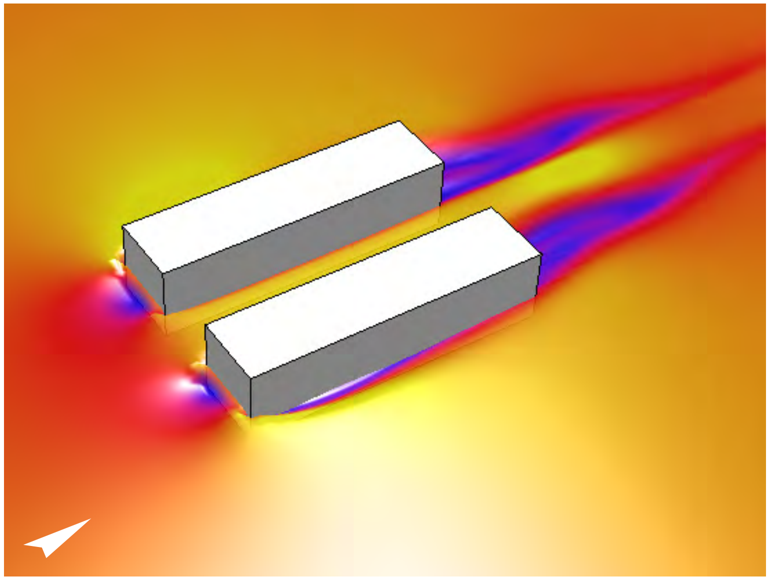
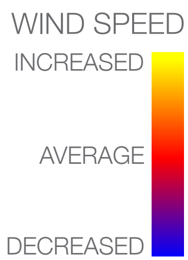


Fig. 3.8. Vasari simulation.



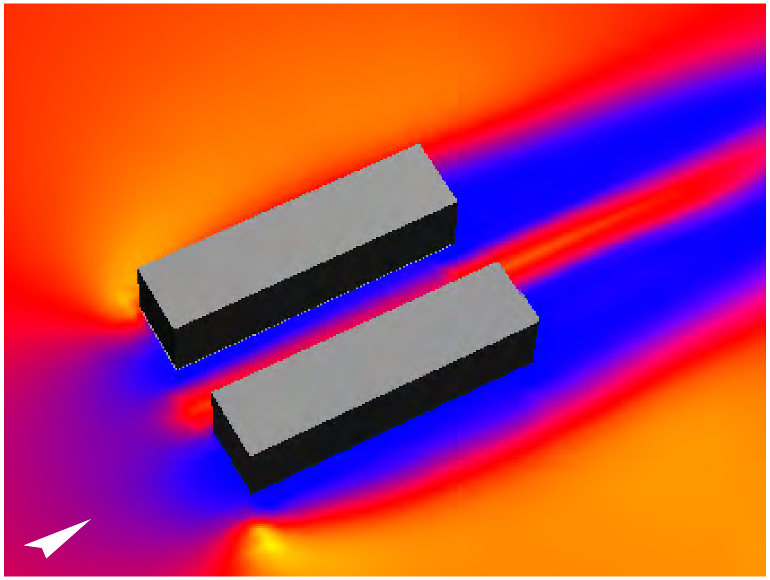


Fig. 3.9. Flow Design simulation.

COMBINED ROW AND DOWNWASH EFFECT

INCREASE WIND SPEED

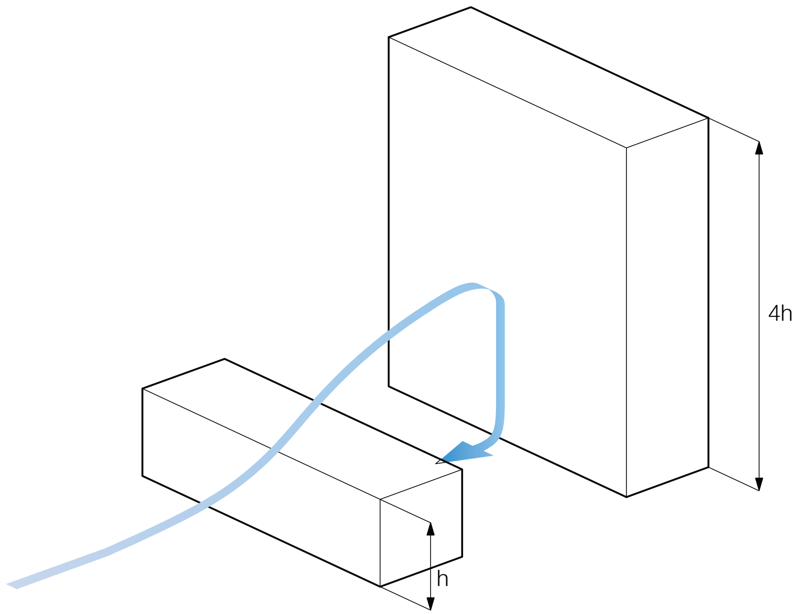
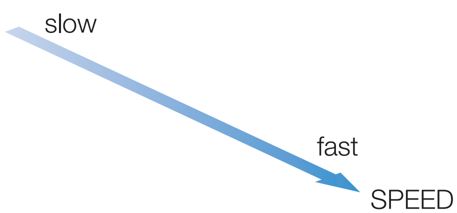
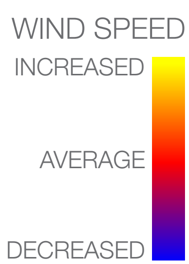


Fig. 3.10. Combined row and downwash effect.





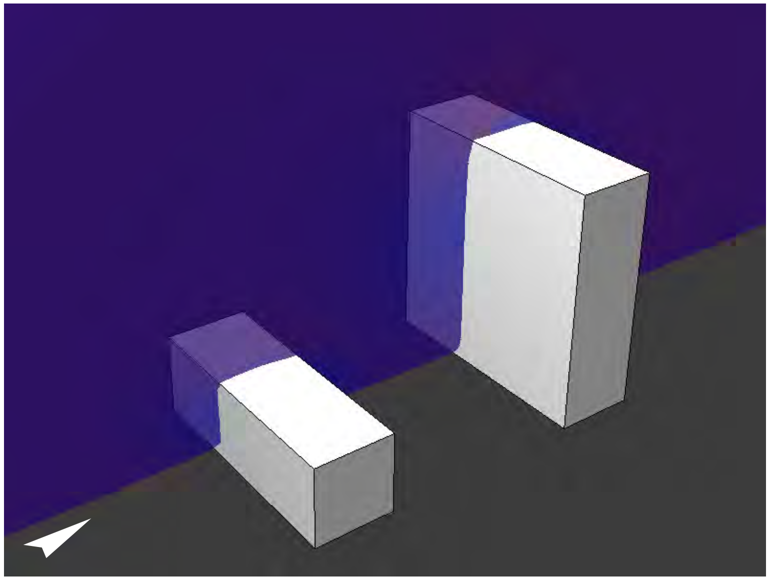


Fig. 3.11. Vasari simulation - effect not shown.

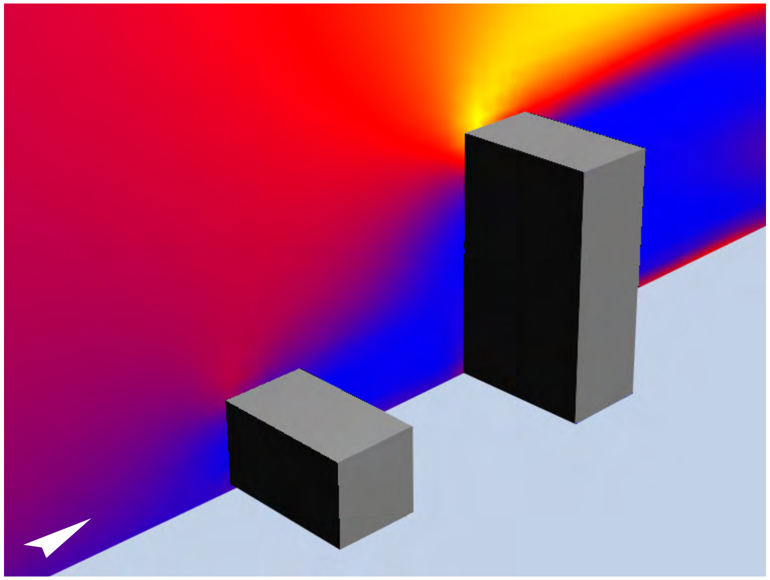


Fig. 3.12. Flow Design simulation - effect not shown.

CORNER EFFECT

INCREASE WIND SPEED

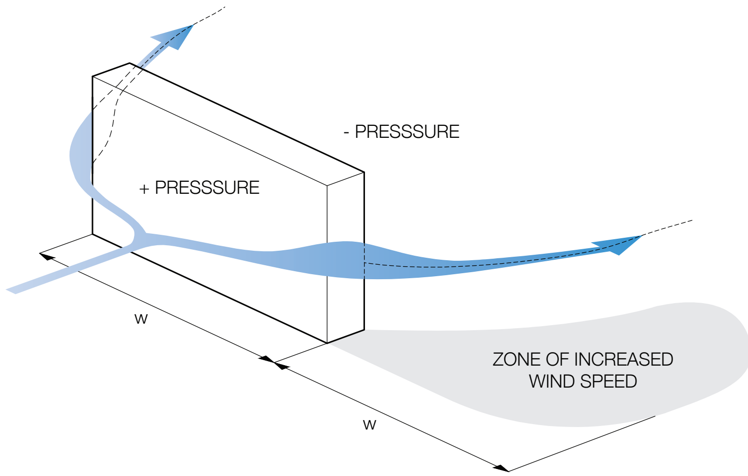


Fig. 3.13. Corner effect.

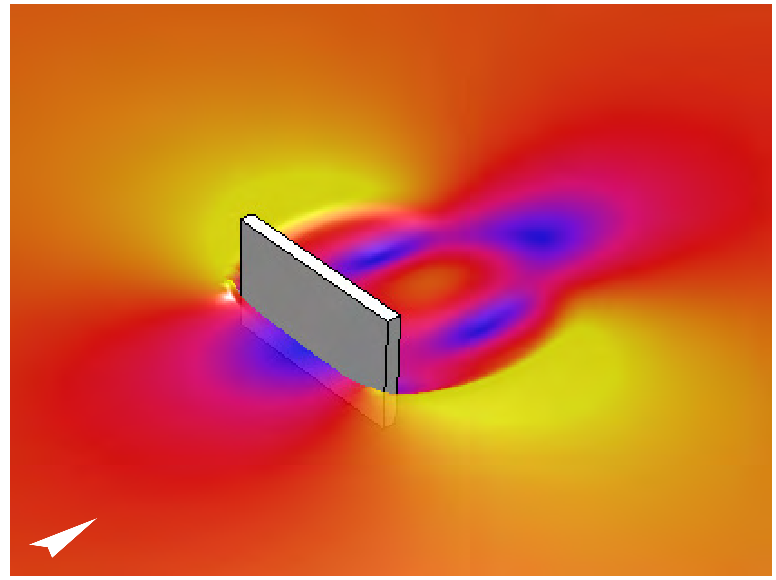
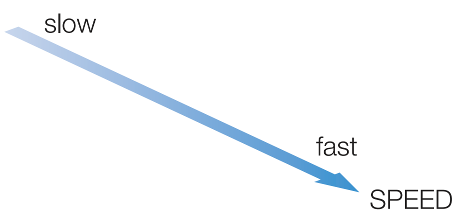
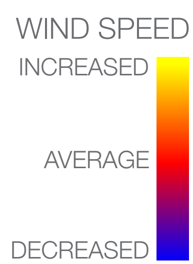


Fig. 3.14. Vasari simulation.





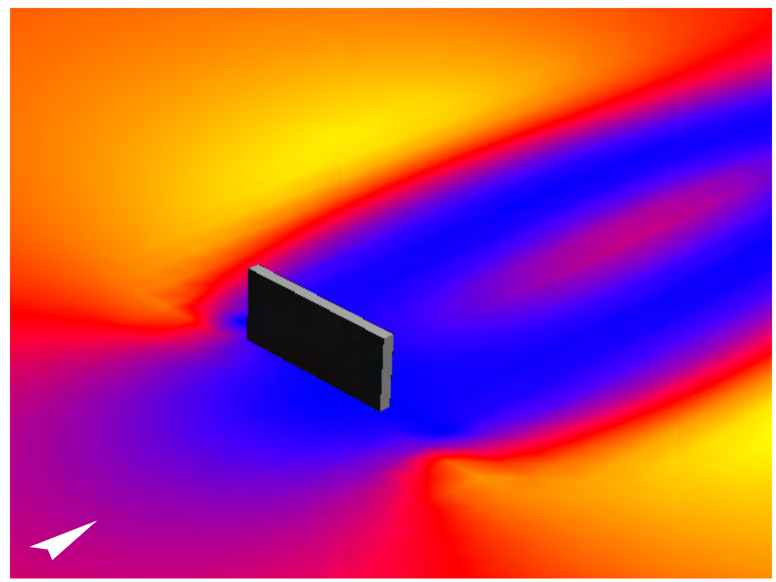


Fig. 3.15. Flow Design simulation.

CUMULATIVE EFFECT
INCREASE WIND SPEED

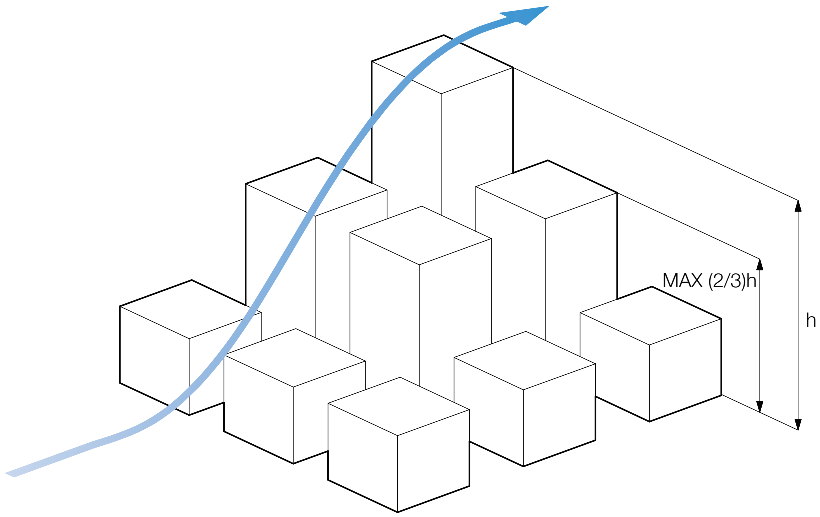
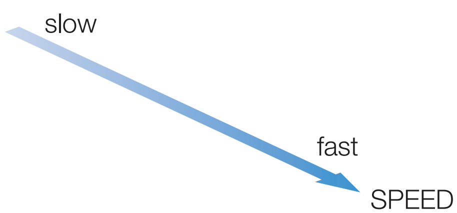
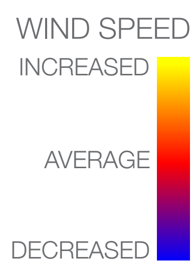


Fig. 3.16. Cumulative effect.





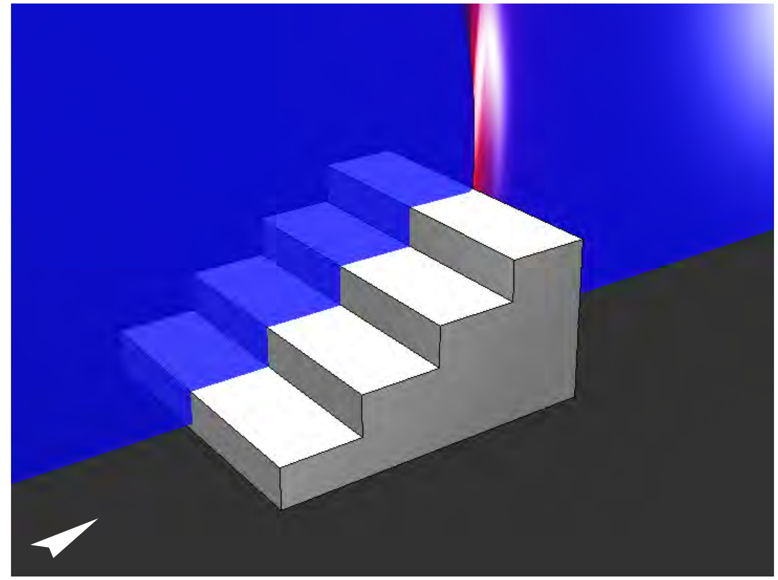


Fig. 3.17. Vasari simulation - effect not shown.

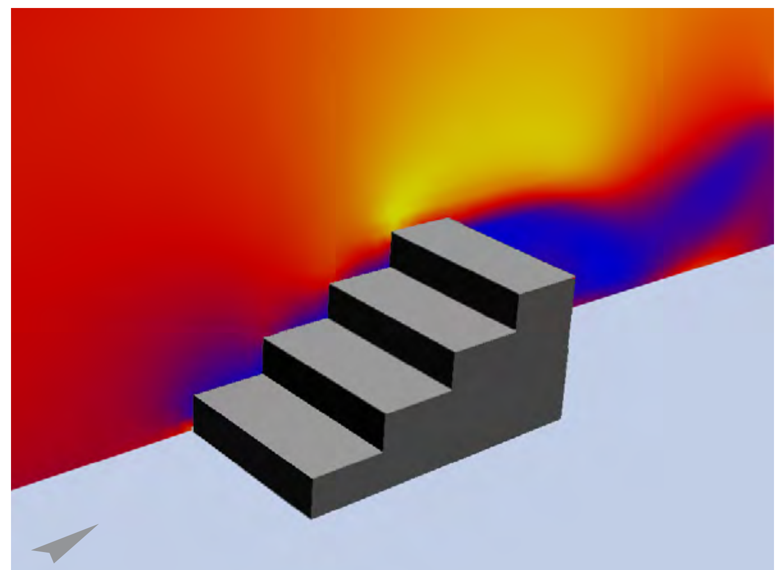


Fig. 3.18. Flow Design simulation.

DIVERTING EFFECT
INCREASE WIND SPEED

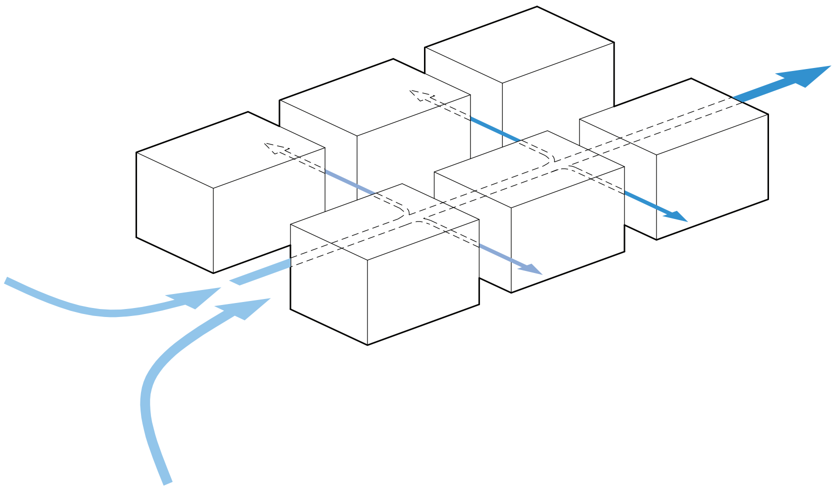


Fig. 3.19. Diverting effect.

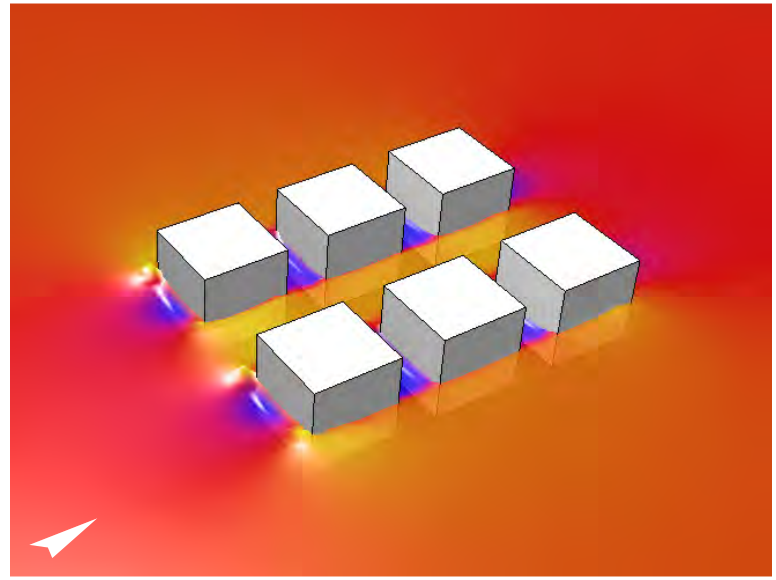
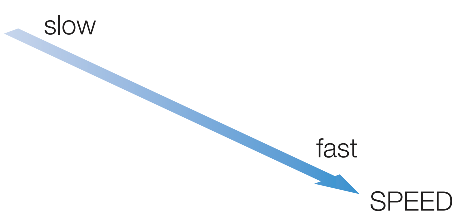
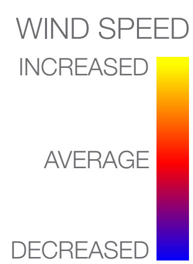


Fig. 3.20. Vasari simulation - effect not shown.





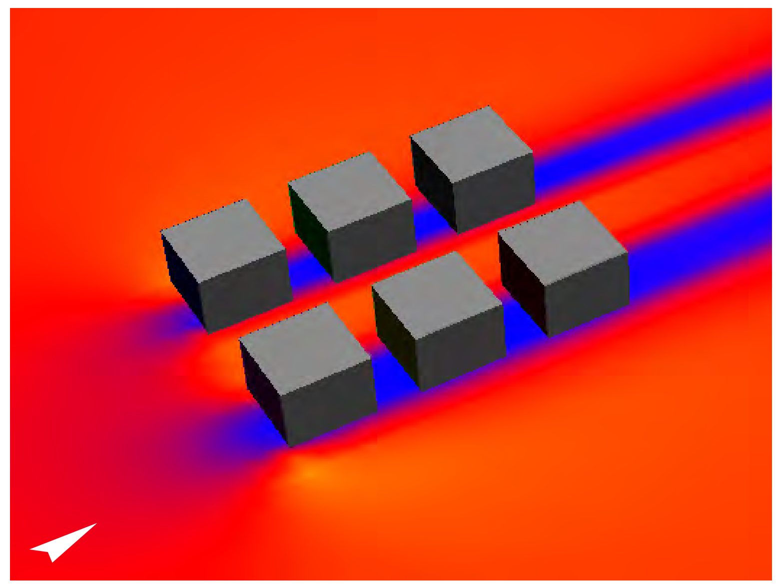


Fig. 3.21. Flow Design simulation - effect not shown.

DOWNWASH EFFECT
INCREASE WIND SPEED

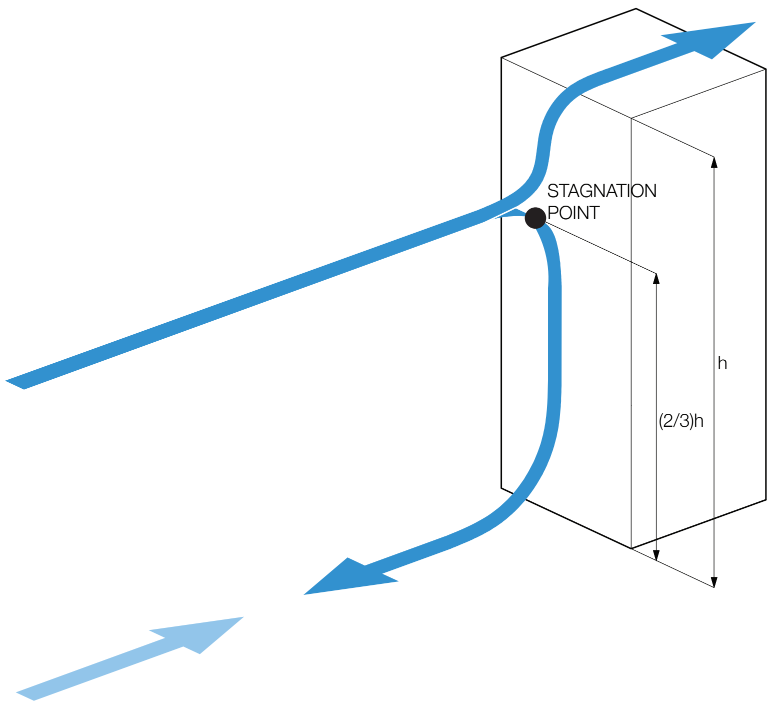
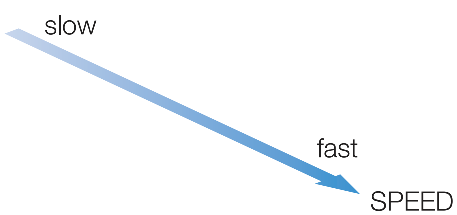
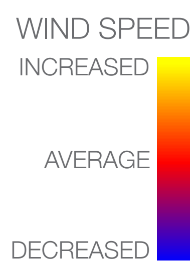


Fig. 3.22. Downwash effect.





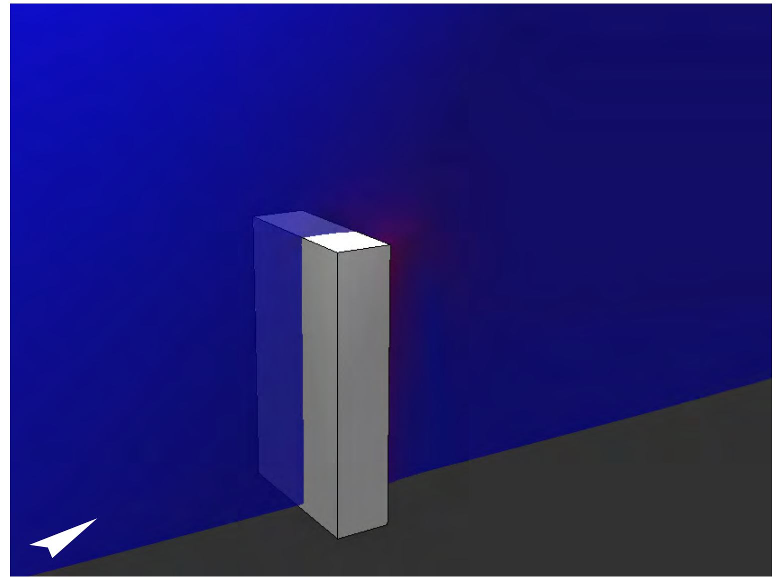


Fig. 3.23. Vasari simulation - effect not shown.

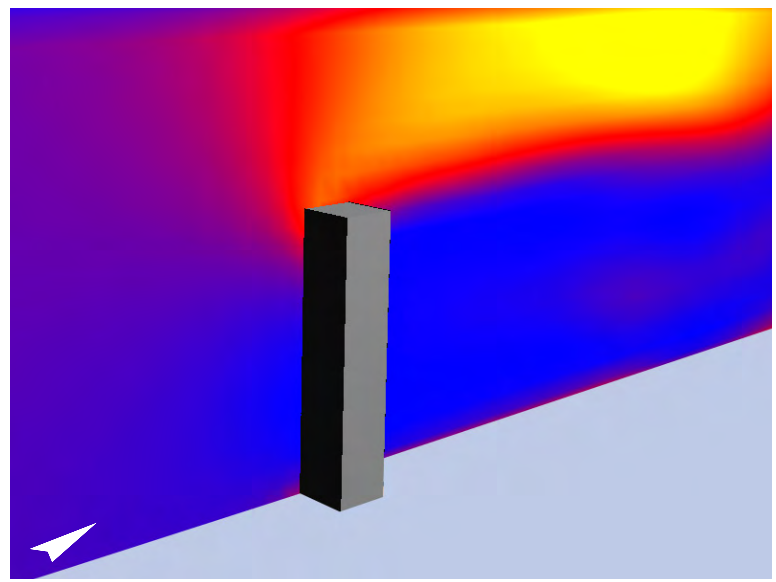


Fig. 3.24. Flow Design simulation - effect not shown.

FUNNELING EFFECT
INCREASE WIND SPEED

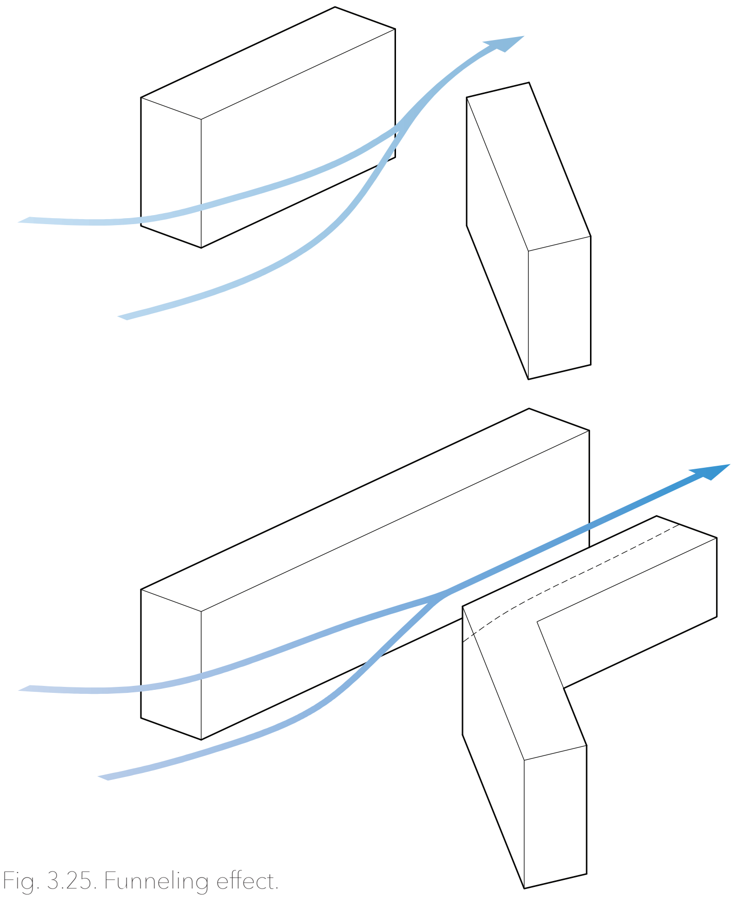
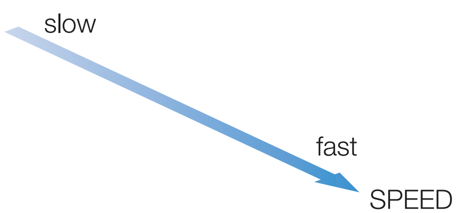


Fig. 3.25. Funneling effect.



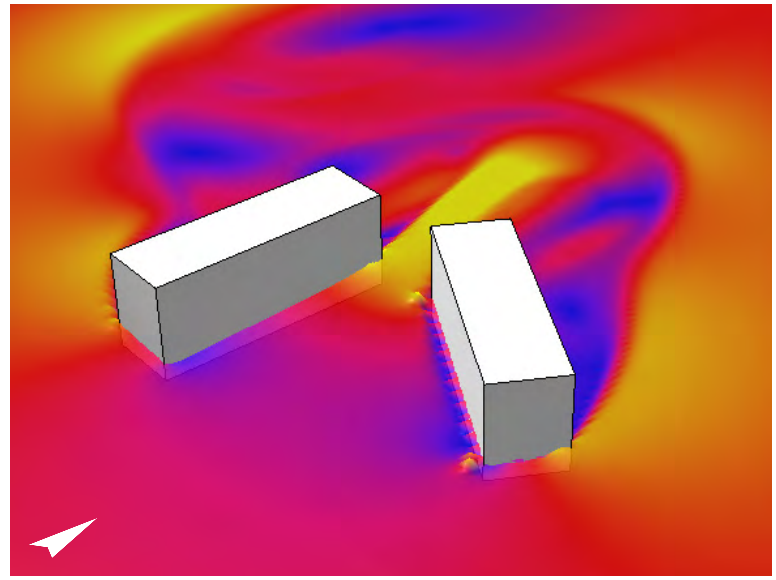
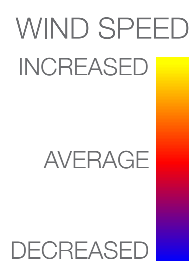


Fig. 3.26. Vasari simulation.



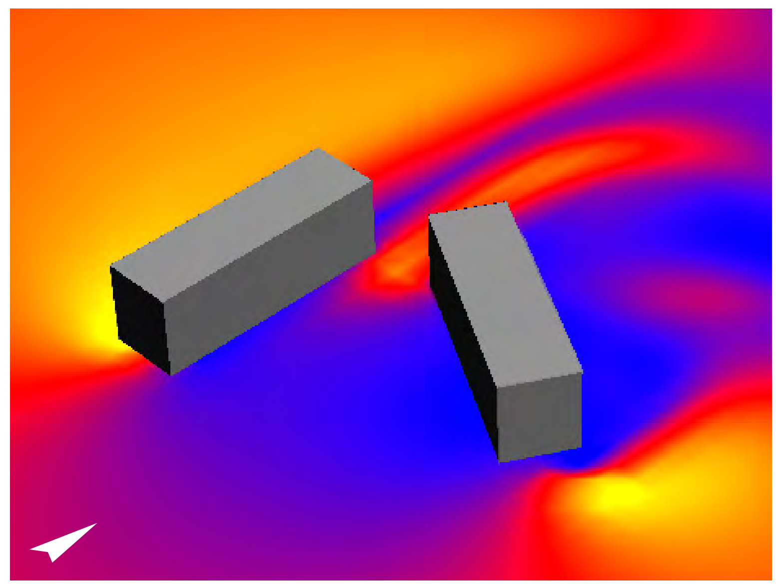


Fig. 3.27. Flow Design simulation.

STAGGERING EFFECT
INCREASE WIND SPEED

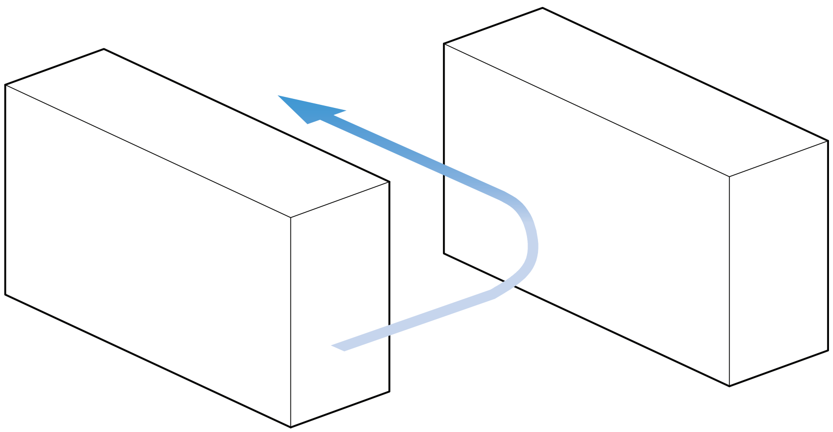


Fig. 3.28. Staggering effect.

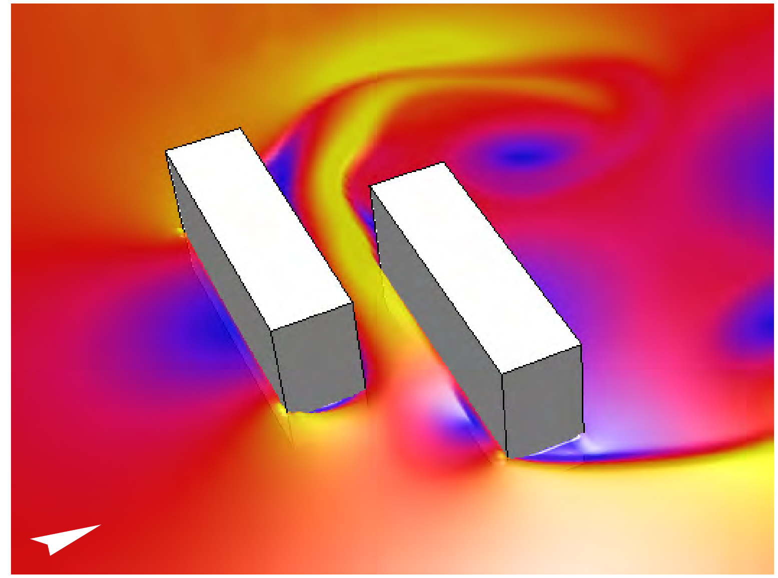
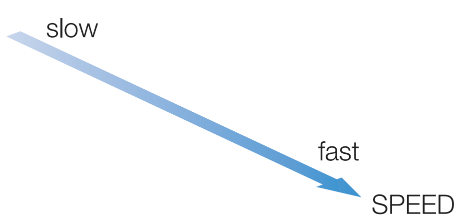
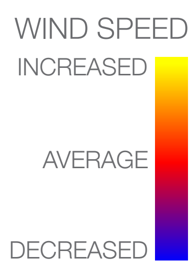


Fig. 3.29. Vasari simulation.





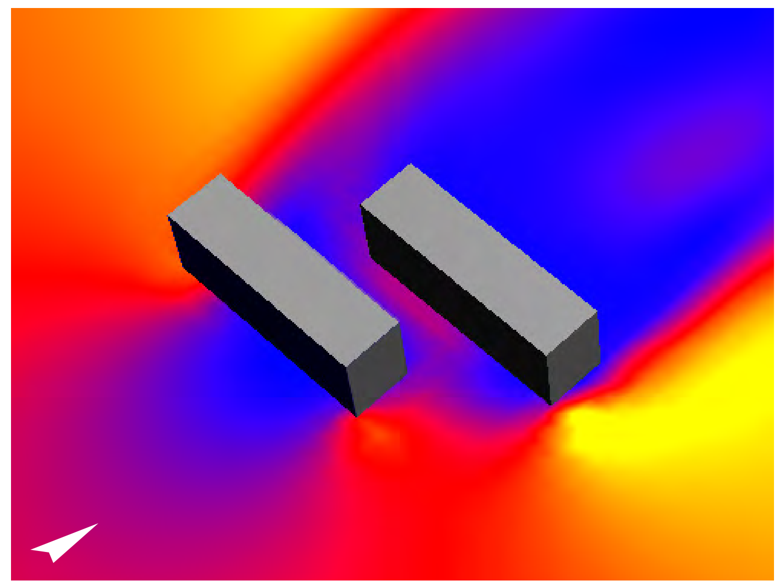


Fig. 3.30. Flow Design simulation - effect not shown.

VENTURI EFFECT
INCREASE WIND SPEED

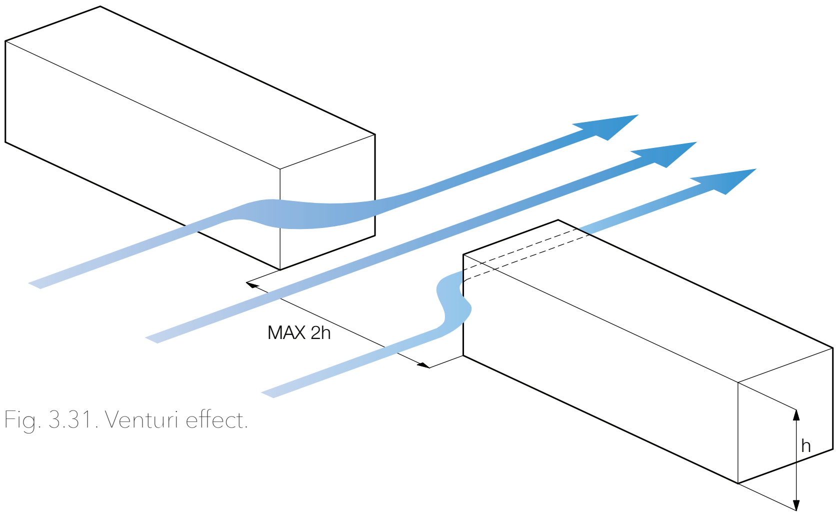


Fig. 3.31. Venturi effect.

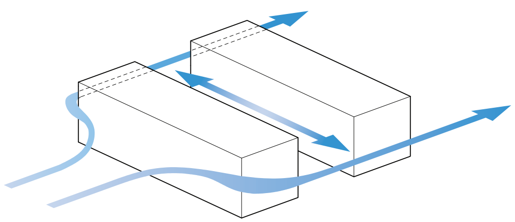
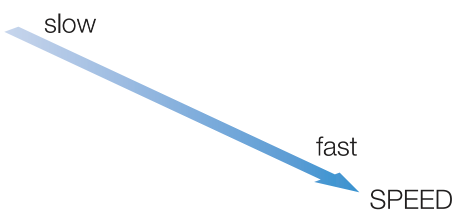


Fig. 3.32. Venturi effect induces suction.



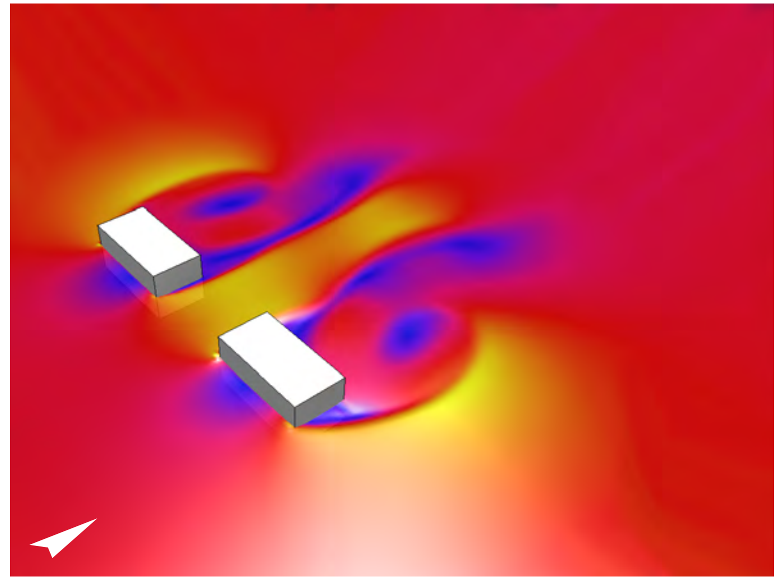
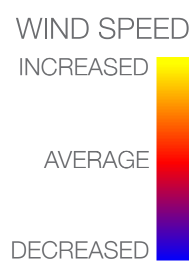


Fig. 3.33. Vasari simulation.



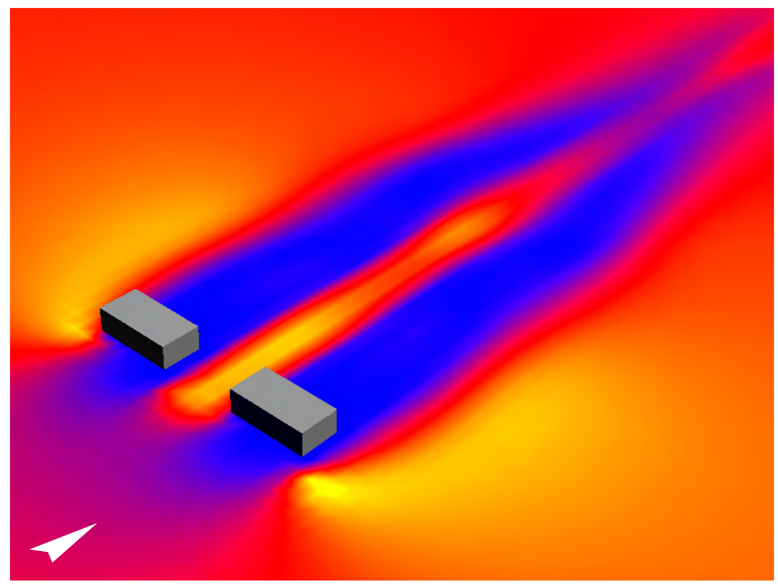


Fig. 3.34. Flow Design simulation.

CUMULATIVE EFFECT
DECREASE WIND SPEED

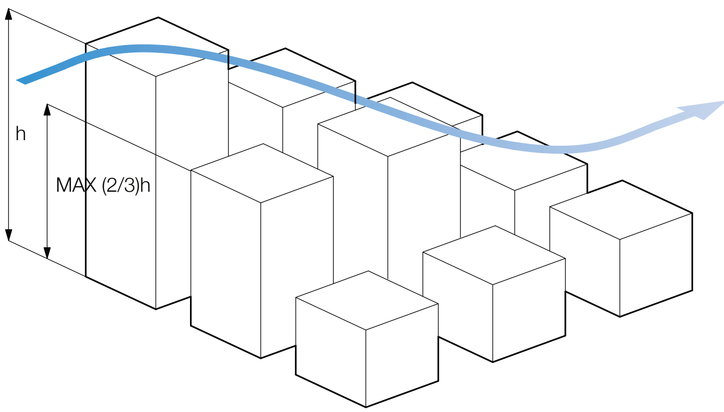


Fig. 3.35. Cumulative effect.

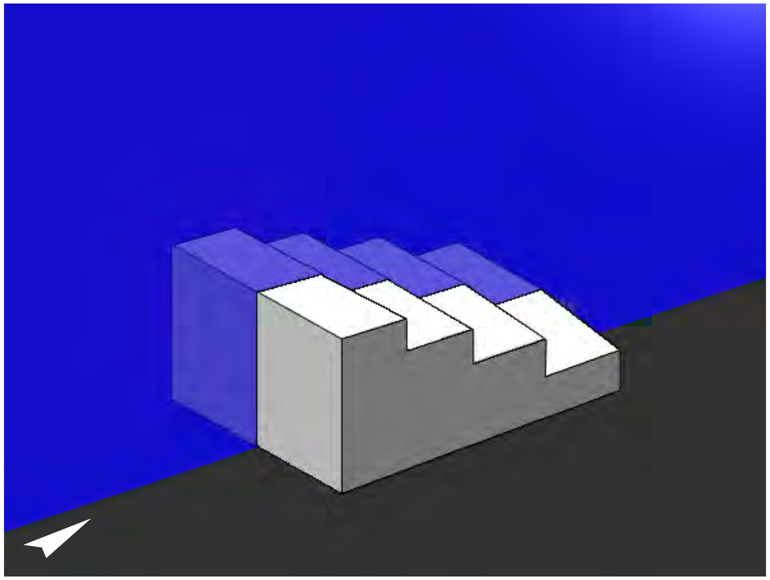
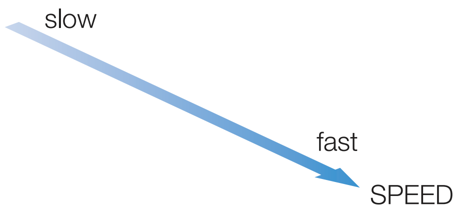
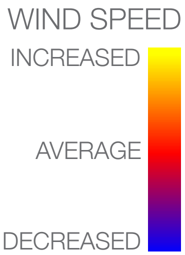


Fig. 3.36. Vasari simulation - effect not shown.





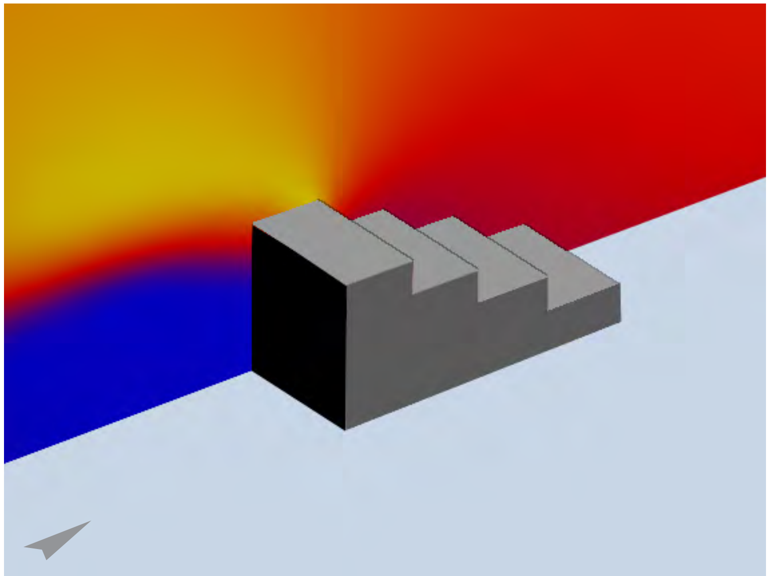


Fig. 3.37. Flow Design simulation - effect not shown.

POROUS WINDBREAK EFFECT
DECREASE WIND SPEED

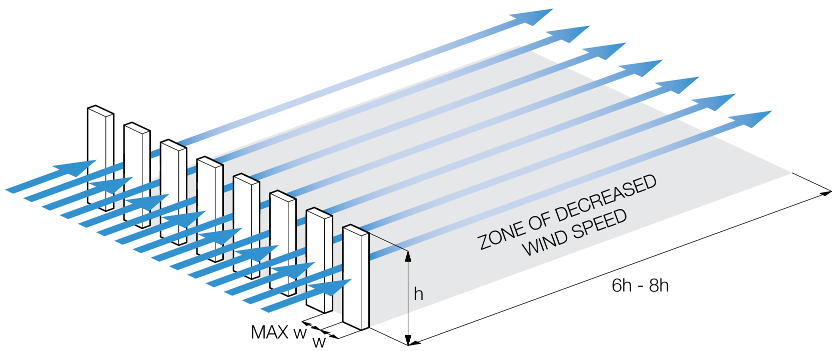
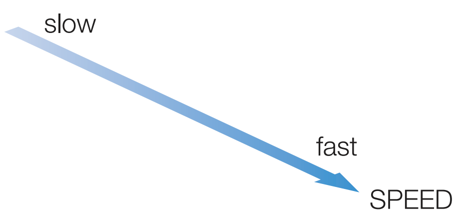


Fig. 3.38. Porous windbreak effect.



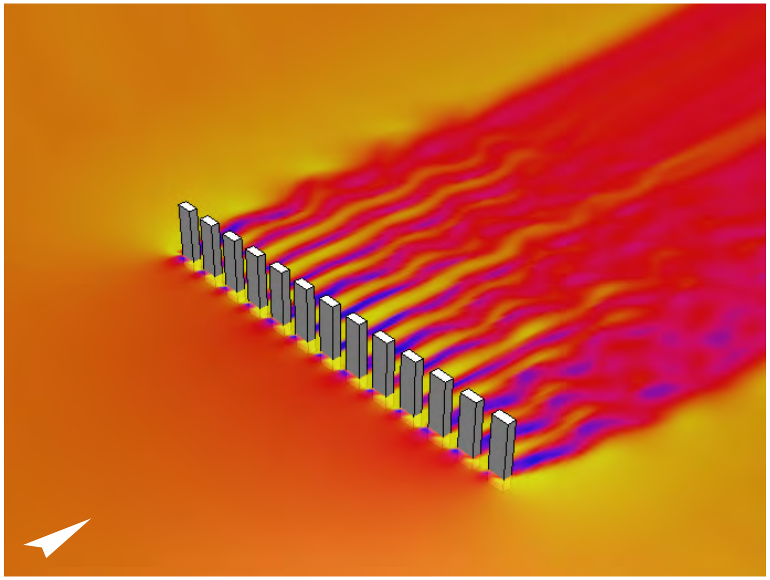


Fig. 3.39. Vasari simulation.

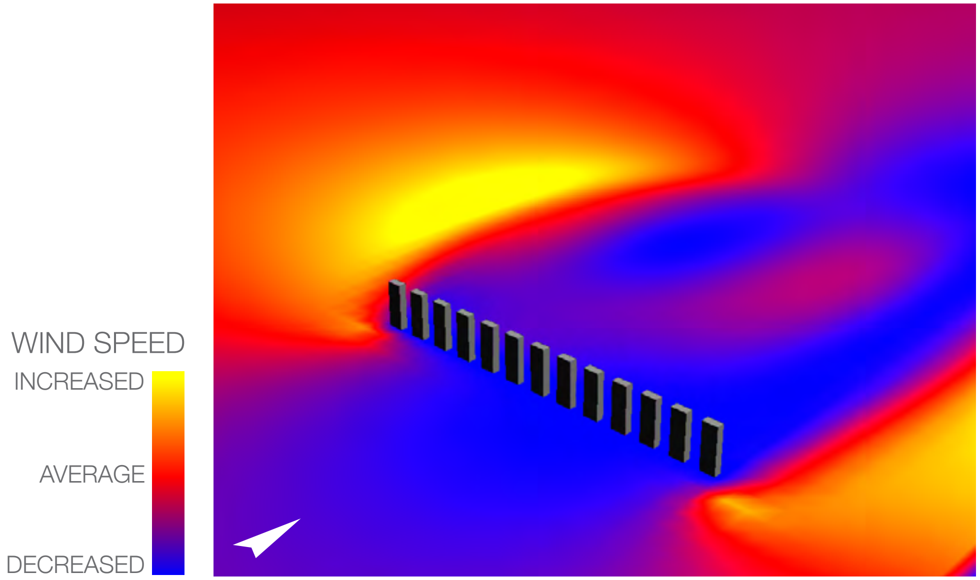


Fig. 3.40. Flow Design simulation.

REDUCTION OF DOWNWASH EFFECT

DECREASE WIND SPEED

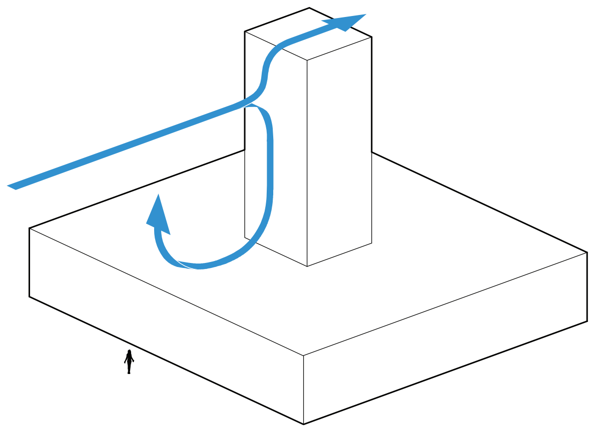


Fig. 3.41. Reduction of downwash effect - podium.

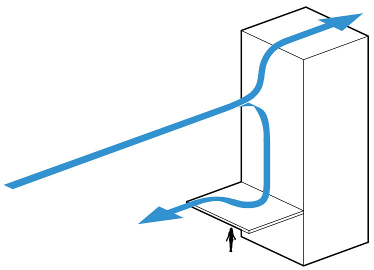


Fig. 3.42. Reduction of downwash effect - canopy.

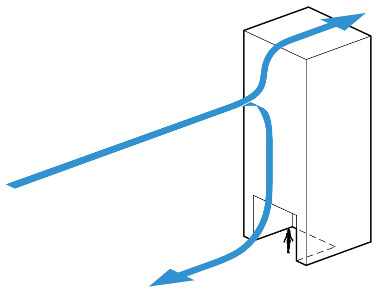
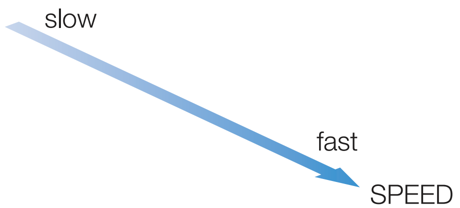


Fig. 3.43. Reduction of downwash effect - setback.



WIND SPEED

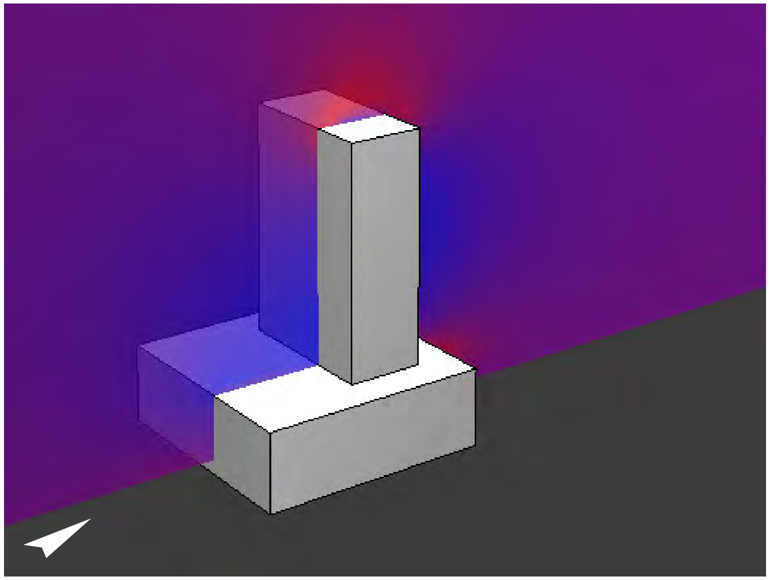


Fig. 3.44. Vasari simulation - effect not shown.

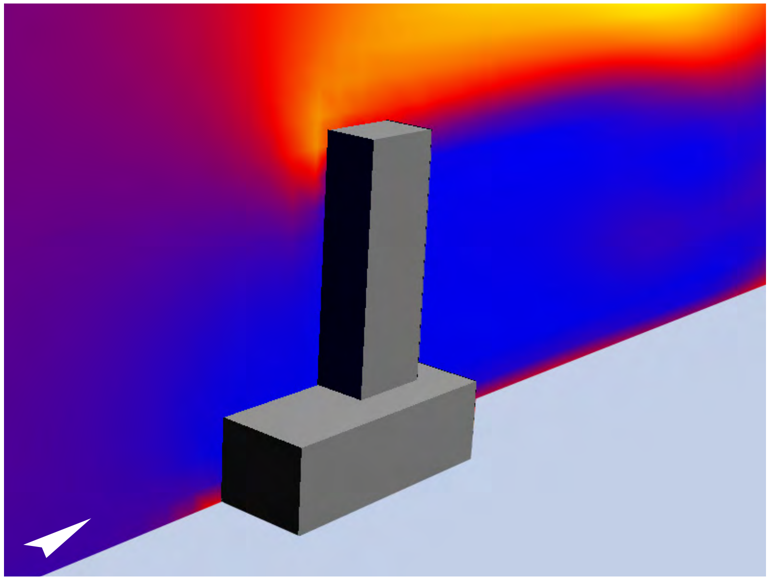


Fig. 3.45. Flow Design simulation - effect not shown.

SOLID WINDBREAK EFFECT
DECREASE WIND SPEED

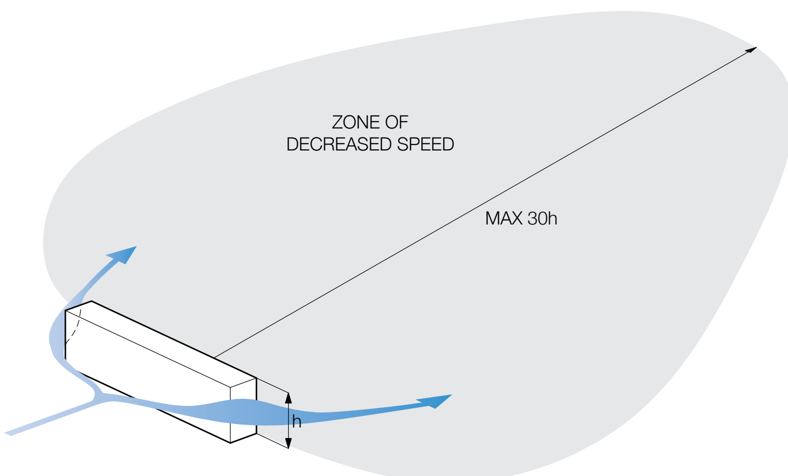
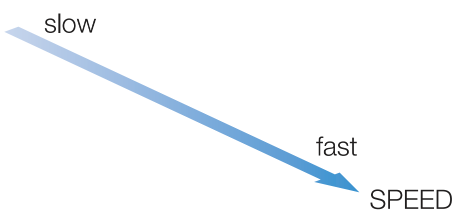


Fig. 3.46. Solid windbreak effect.



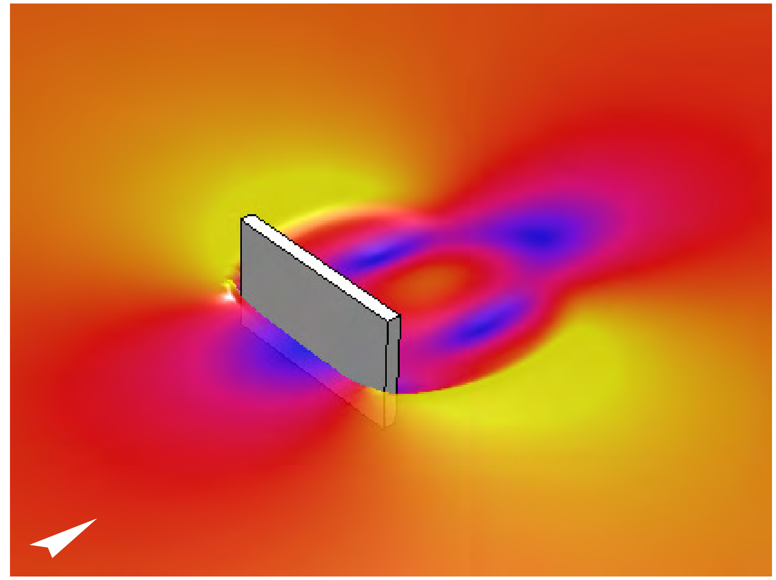
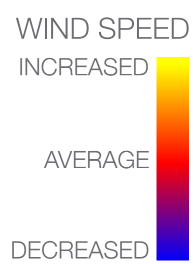


Fig. 3.47. Vasari simulation.



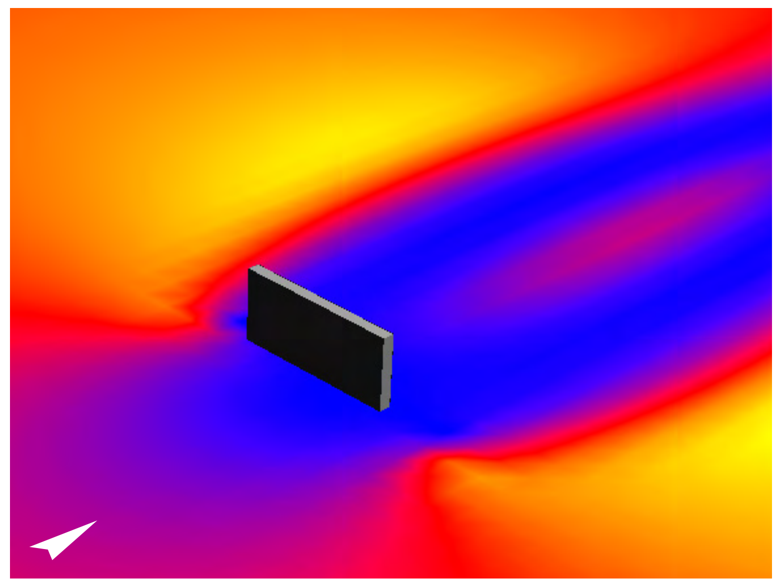


Fig. 3.48. Flow Design simulation.

COMBINED ROW AND DOWNWASH EFFECT

INCREASE WIND TURBULENCE

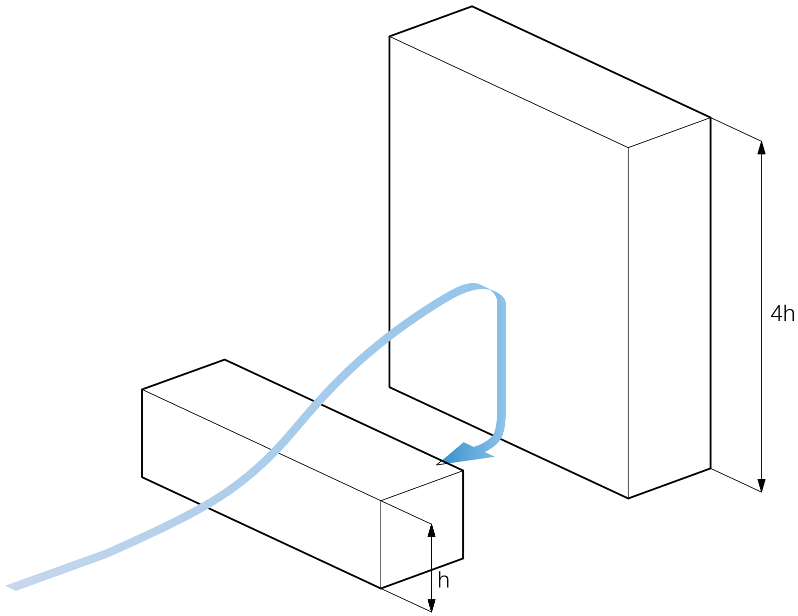


Fig. 3.49. Combined row and downwash effect.

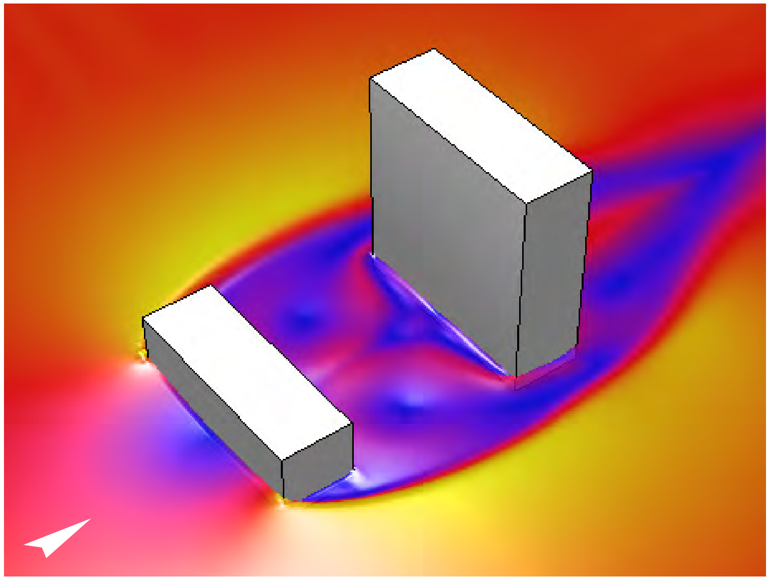
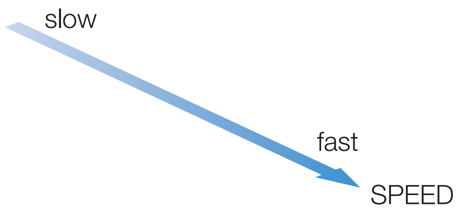
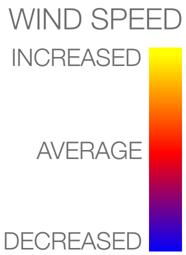


Fig. 3.50. Vasari simulation.





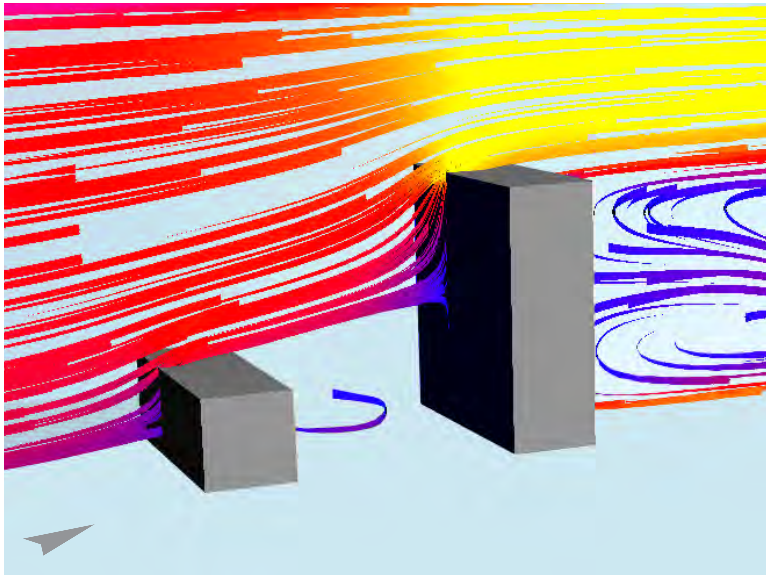


Fig. 3.51. Flow Design simulation.

COURTYARD EFFECT

INCREASE WIND TURBULENCE

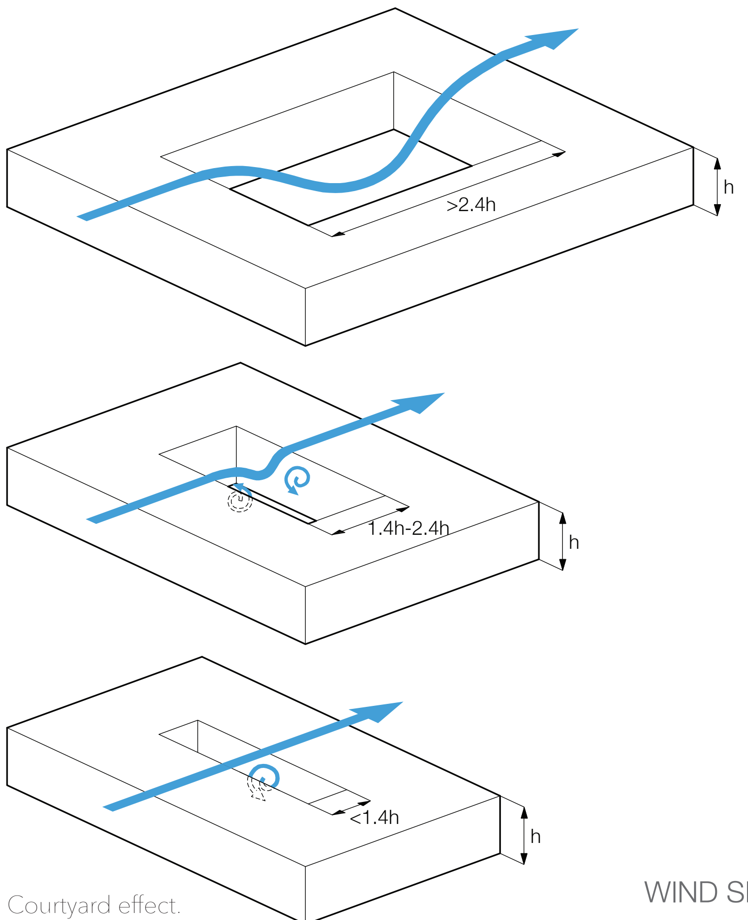
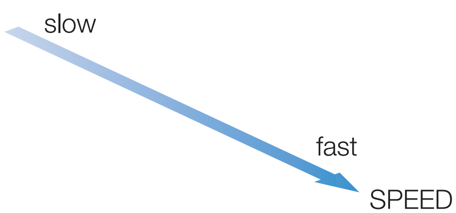
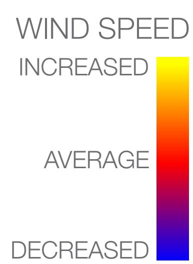


Fig. 3.52. Courtyard effect.





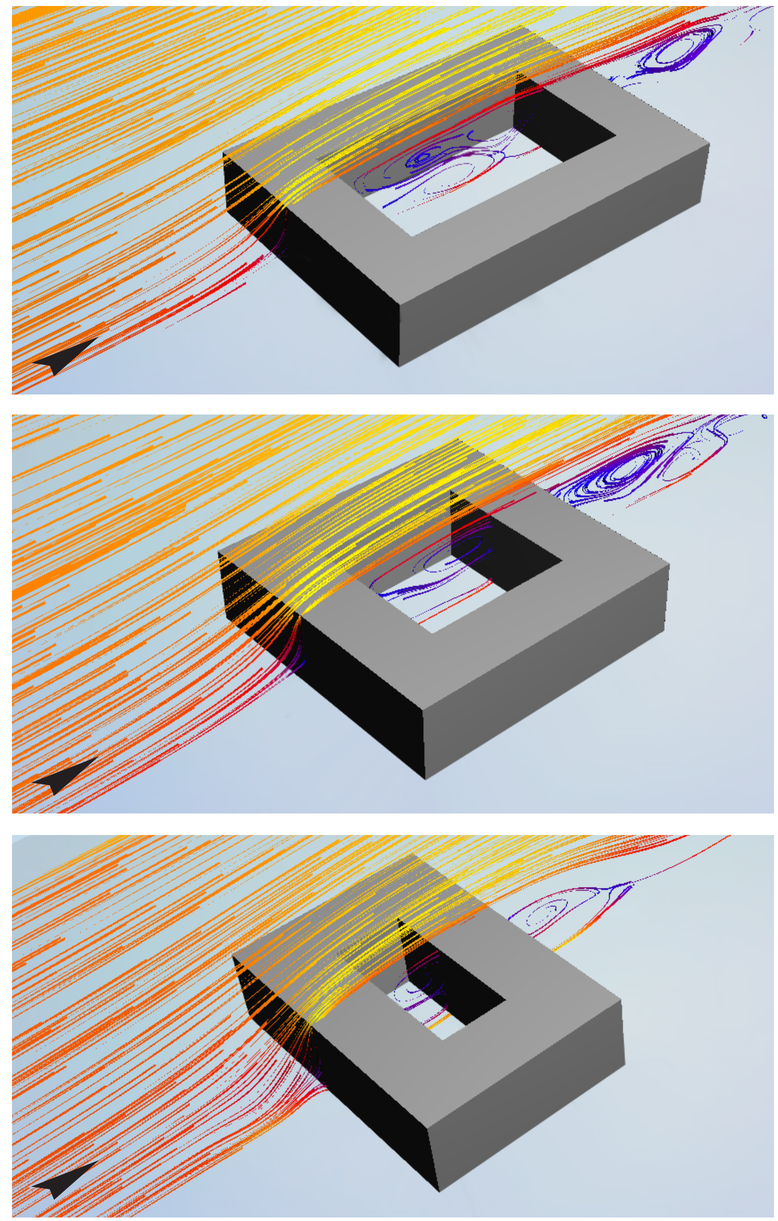


Fig. 3.53. Flow Design simulation (effect not shown in Vasari).

DOWNWASH EFFECT
INCREASE WIND TURBULENCE

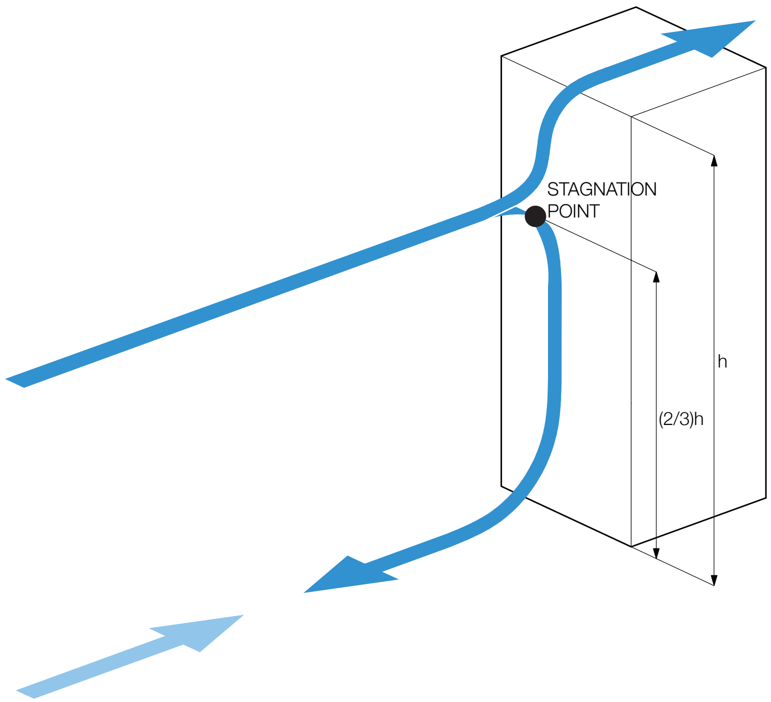
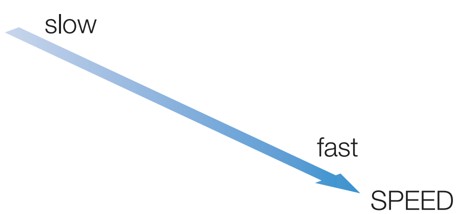
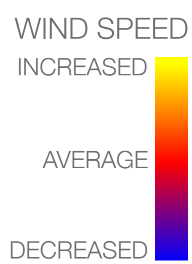


Fig. 3.54. Downwash effect.





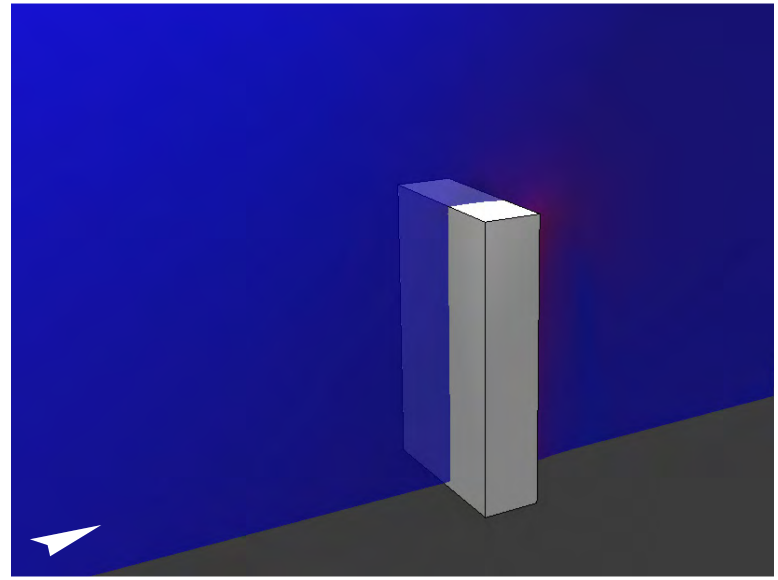


Fig. 3.55. Vasari simulation - effect not shown.

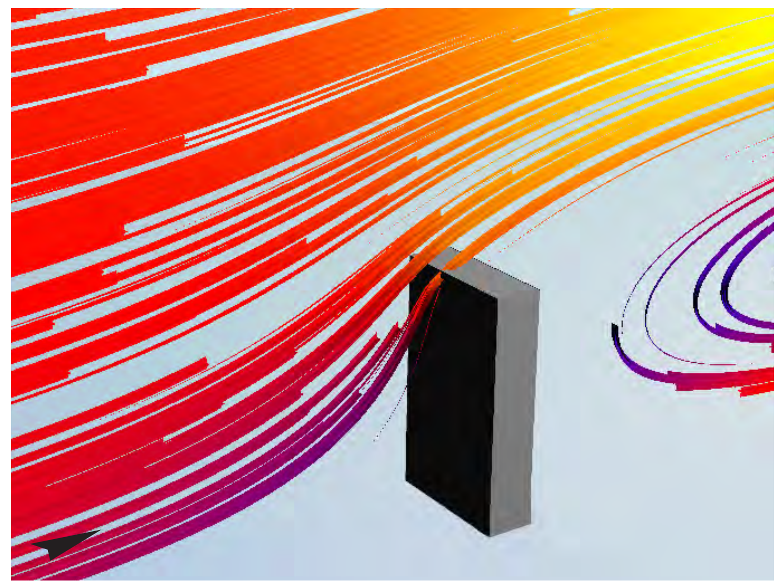


Fig. 3.56. Flow Design simulation - effect not shown.

ROW EFFECT
INCREASE WIND TURBULENCE

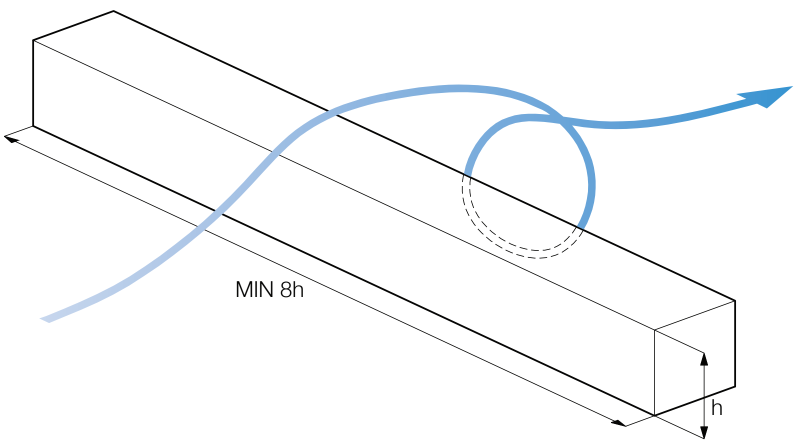


Fig. 3.57. Row effect.

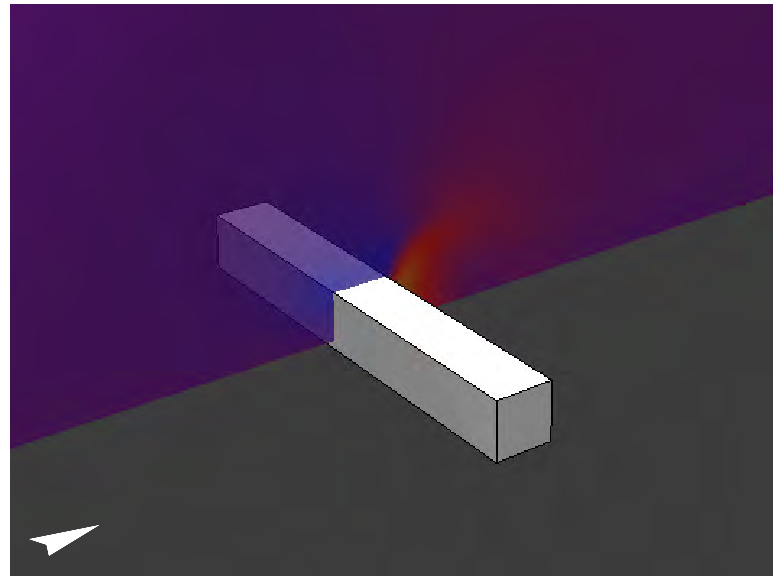


Fig. 3.58. Vasari simulation - effect not shown.

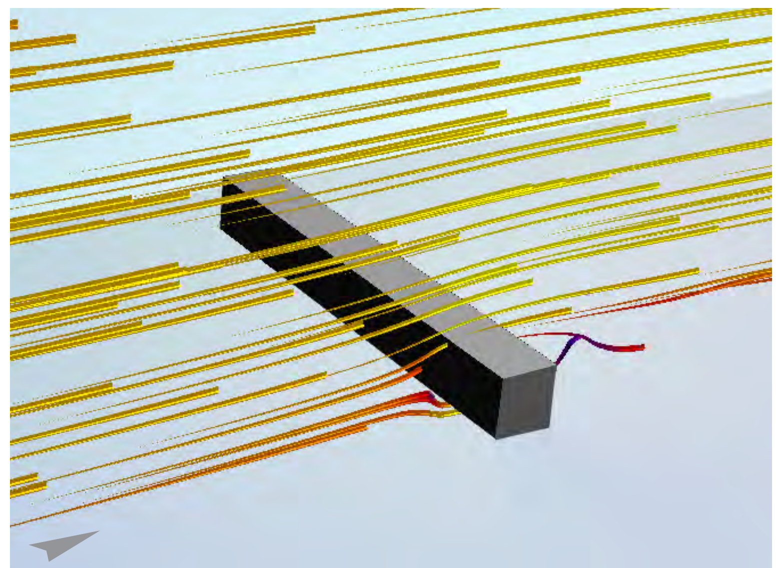
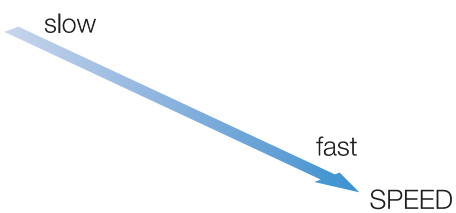
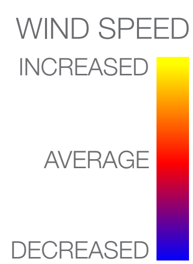


Fig. 3.59. Flow Design simulation.





VORTEX SHEDDING

INCREASE WIND TURBULENCE

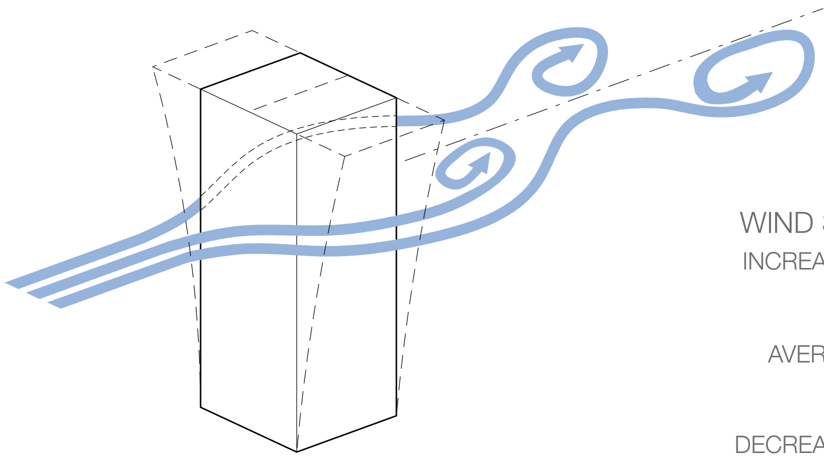


Fig. 3.60. Vortex shedding.

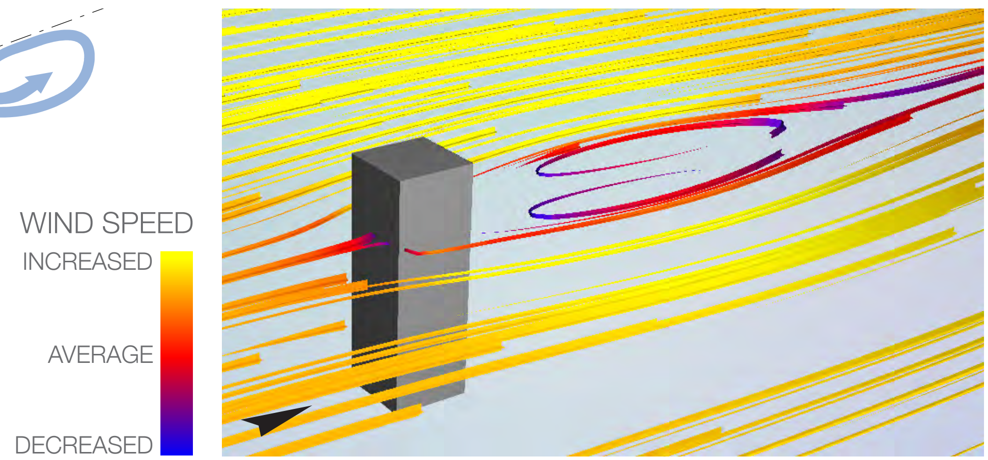
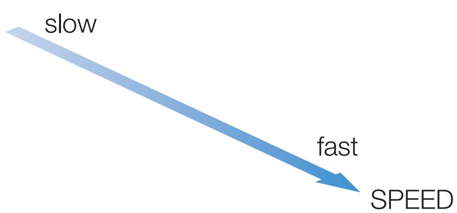


Fig. 3.61. Flow Design simulation (flow lines not shown in Vasari).



WAKE EFFECT
INCREASE WIND TURBULENCE

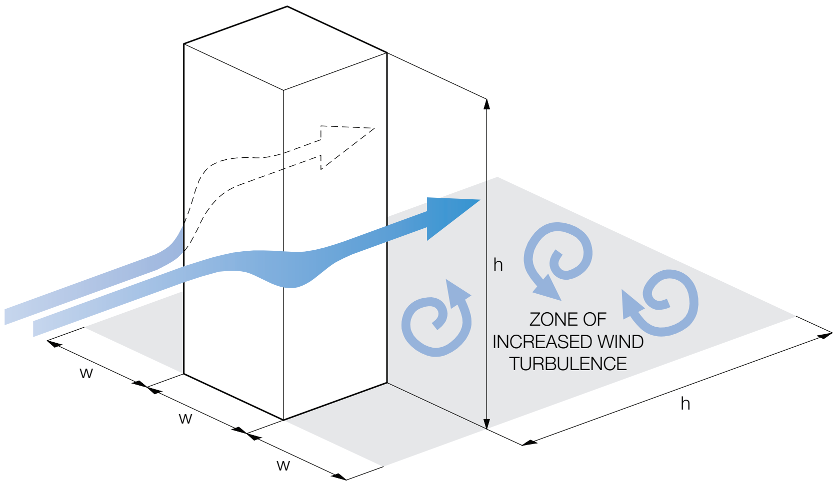
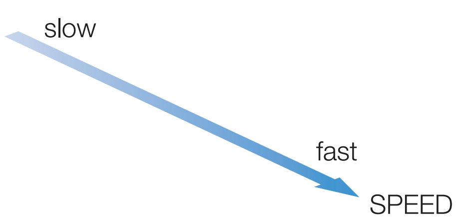


Fig. 3.62. Wake effect.



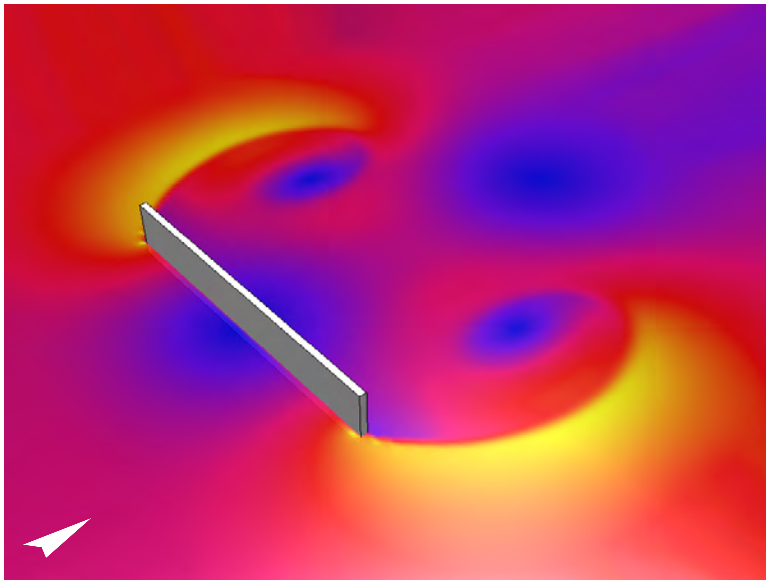


Fig. 3.63. Vasari simulation.

Fig. 3.64. Flow Design simulation.

COURTYARD EFFECT
DECREASE WIND TURBULENCE

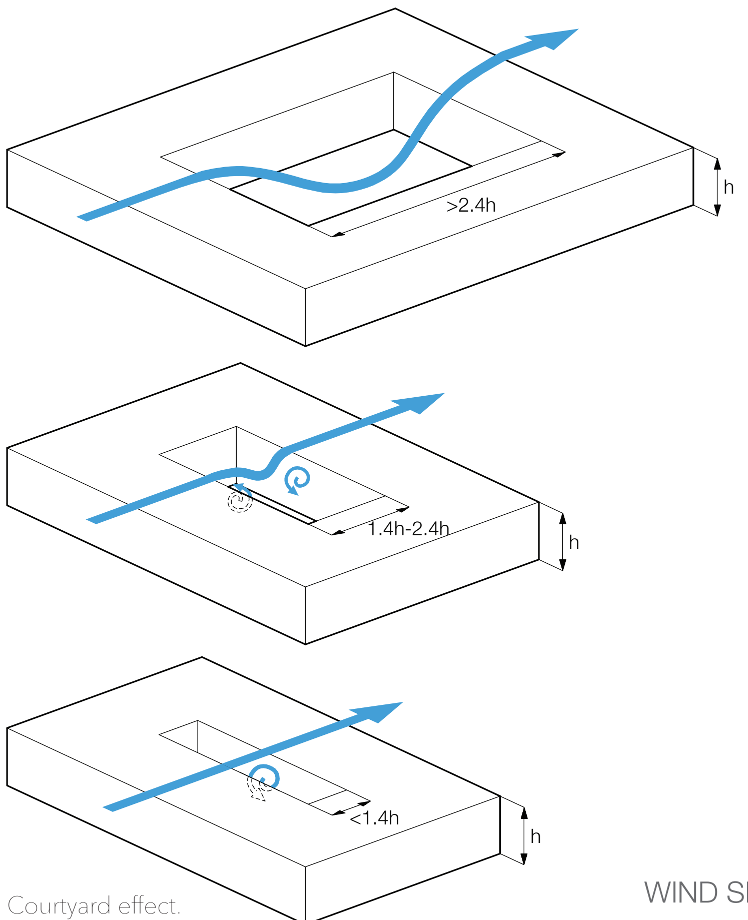
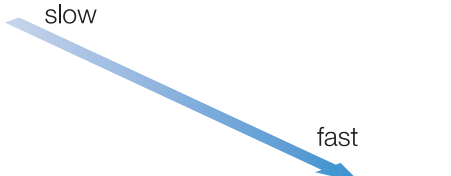


Fig. 3.65. Courtyard effect.



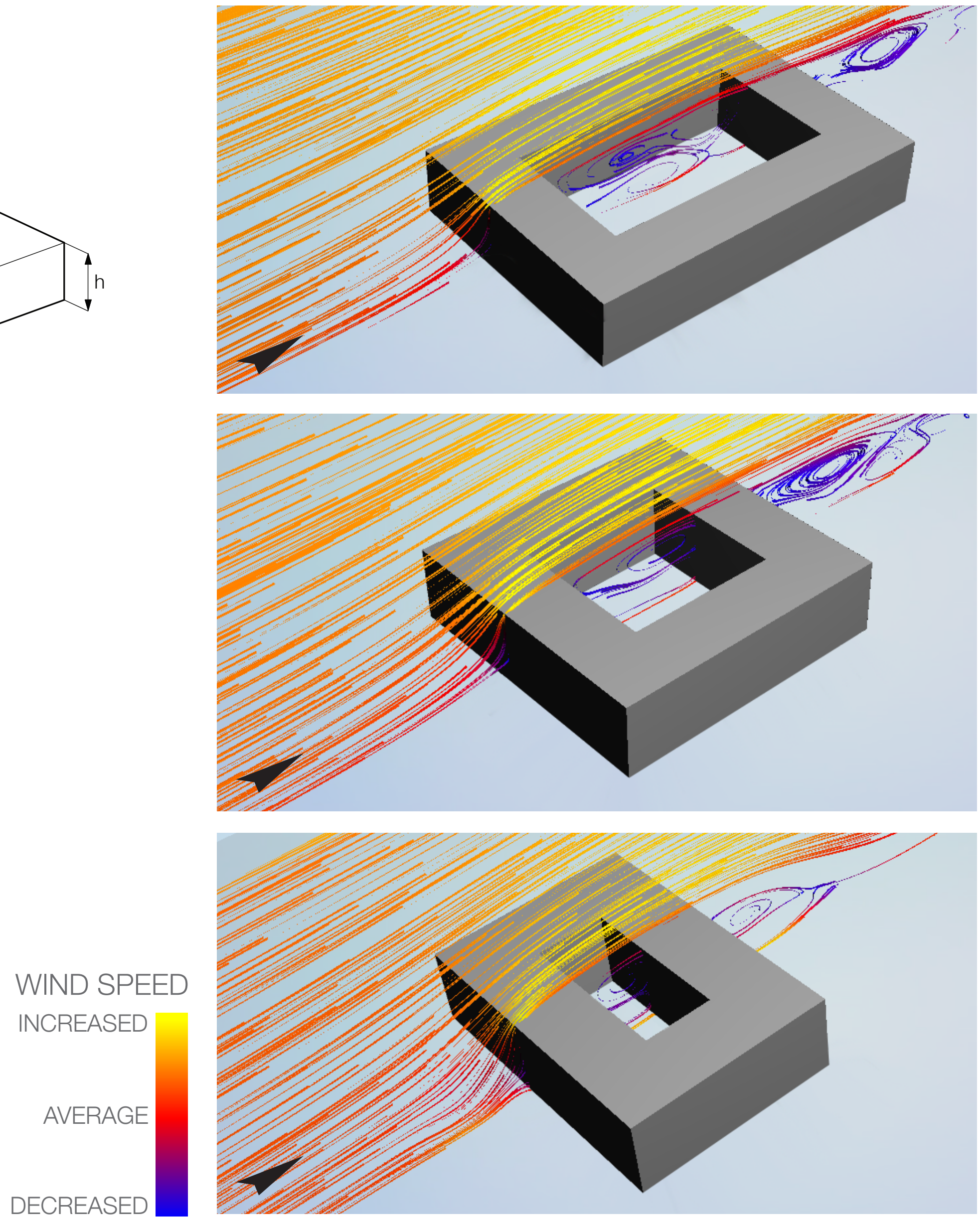


Fig. 3.66. Flow Design simulation (effect not shown in Vasari).

DISTANCE FROM OBSTRUCTION
DECREASE WIND TURBULENCE

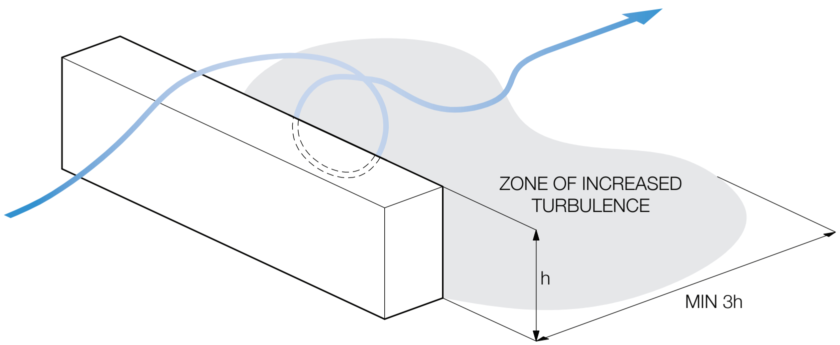


Fig. 3.67. Distance from obstruction.

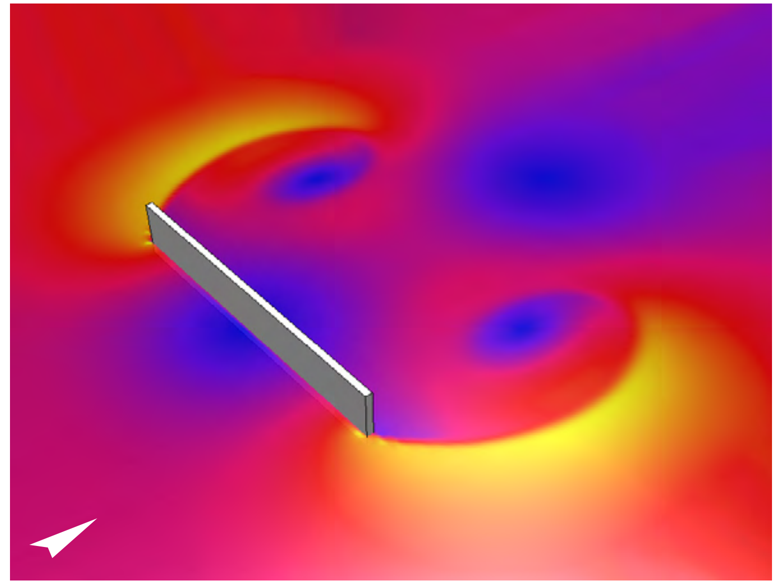


Fig. 3.68. Vasari simulation.

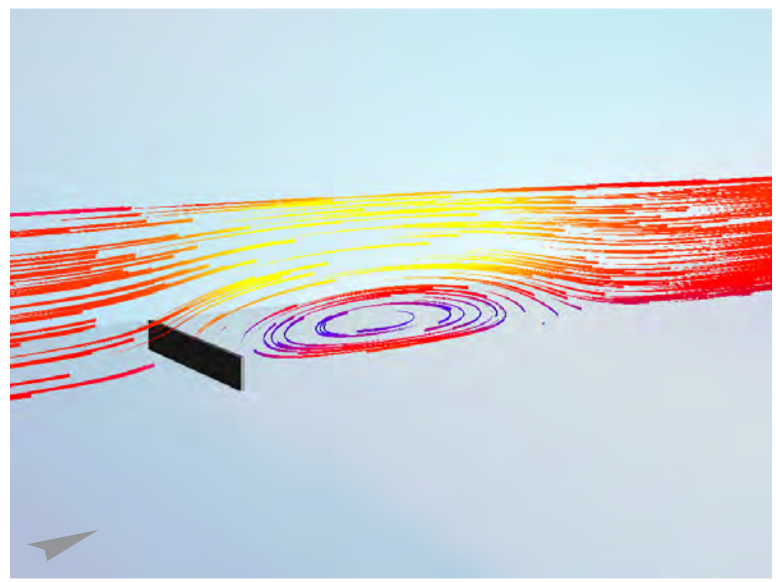
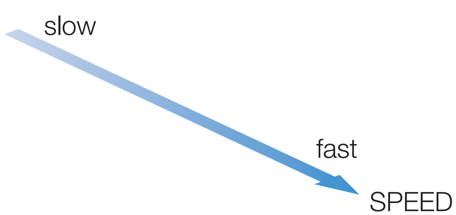
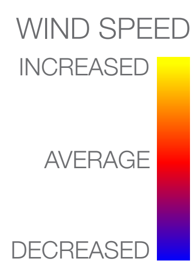


Fig. 3.69. Flow Design simulation.





CFD ITERATIONS TO CREATE WIND CONDITIONS

For the first step in the design method, a building form is modeled and tested with CFD software to visualize the wind speeds and patterns that are created around the building by the building form, and evaluate the appropriateness of these wind conditions for the exterior programs that are intended to be accommodated. This can be represented by Vasari's horizontal data slices of wind speed that depict general wind patterns. After the first building iteration is tested with the CFD software, the architect makes observations and adjusts the form within Vasari for the next iteration to improve the appropriateness of the surrounding wind conditions for the exterior programs. These adjustments to the form may be made by referring to the wind effects library, which catalogues ways of manipulating form to increase or decrease the surrounding wind speed and turbulence. Iterations may also be tested in Flow Design to look at the flow lines, which depict the wind turbulence that is generated by the building. Although this adds an extra step to the process, it is beneficial to ensure that there is no undesired turbulence created by the building form. As CFD programs are improved in the future, the accuracy of this process will increase. To test this first step in the method, a building form was developed through eleven iterations, improving the surrounding wind conditions with each iteration.

WIND FROM MOST PREDOMINANT DIRECTION

The first six iterations were developed while only considering wind coming from the predominant southeast direction. The second-most predominant wind direction on the site was disregarded for these first six iterations to allow the architect to become familiar with the iterative process and the ways in which building form can influence the wind within a simple site condition. These first six iterations are depicted on the following pages.

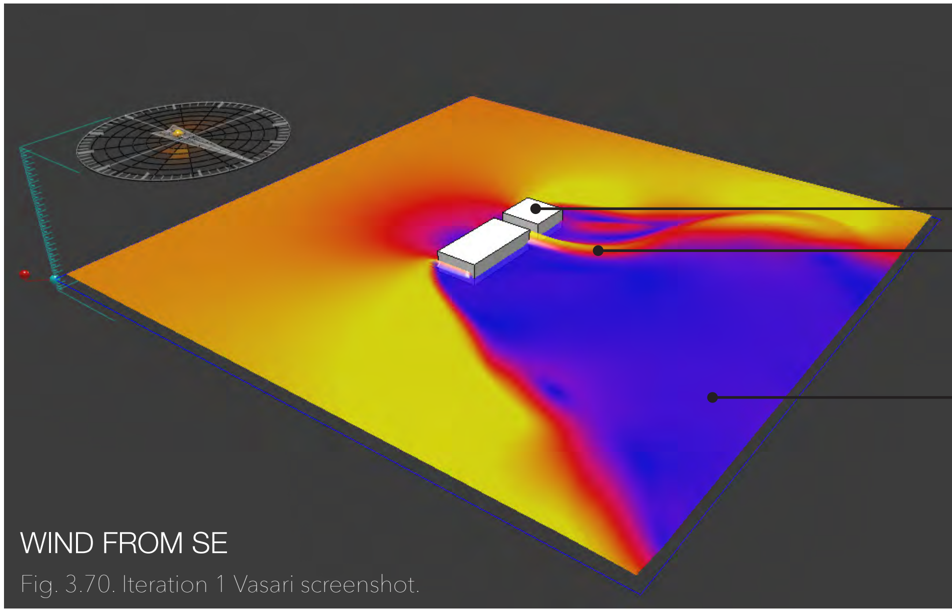


Fig. 3.70. Iteration 1 Vasari screenshot.

ITERATION 1

begin with two volumes to create sheltered areas of decreased wind speed, as well as a channel of increased wind speed between the volumes

channel of increased speed curves towards the shorter form; in next iteration, test forms of the same length to see if it affects the direction of the channel

area of decreased wind speed

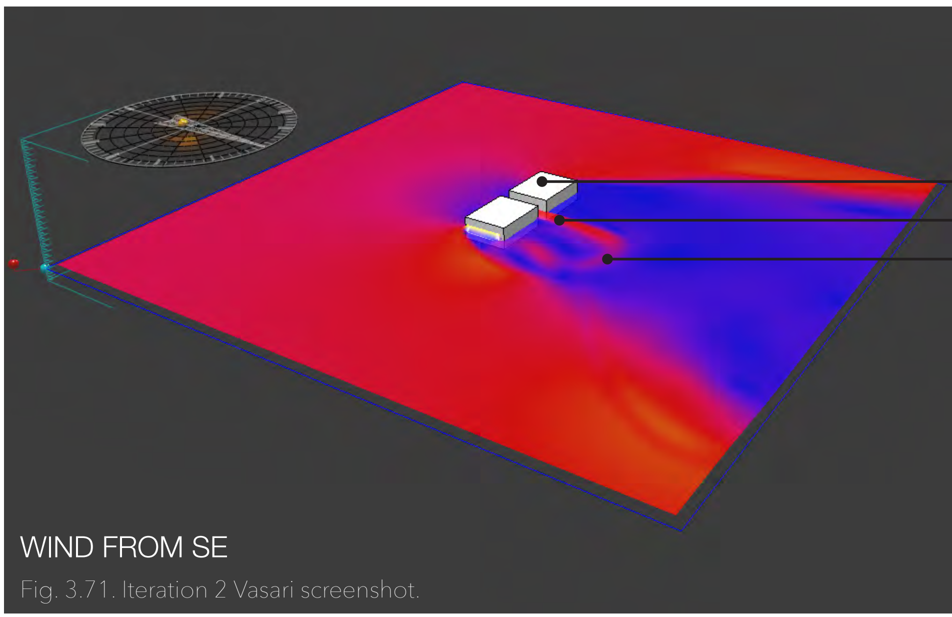


Fig. 3.71. Iteration 2 Vasari screenshot.

ITERATION 2

forms have been made the same length

channel of increased speed has straightened

channel of increased speed is short; in next iteration, see if increasing the space between the forms lengthens the channel

WIND SPEED

INCREASED

AVERAGE

DECREASED

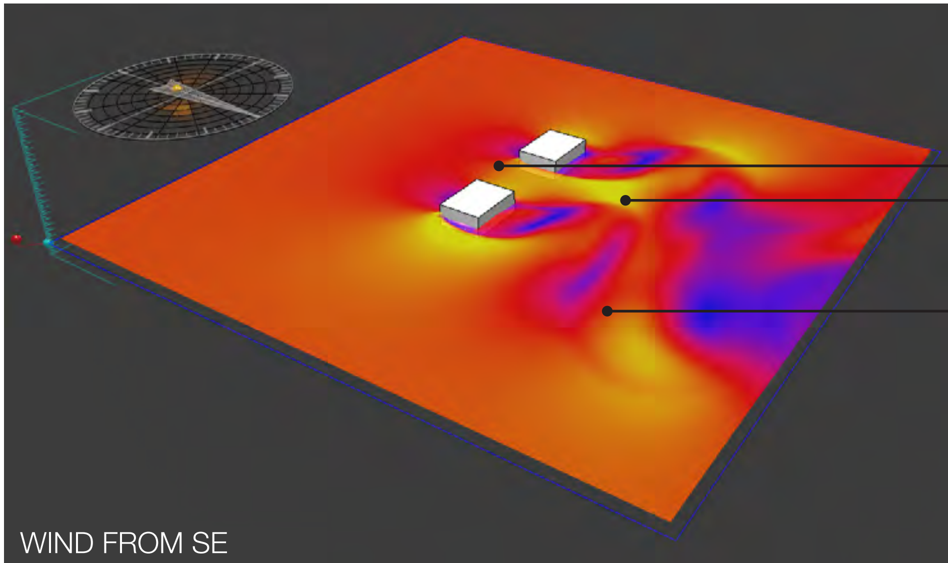


Fig. 3.72. Iteration 3 Vasari screenshot.

ITERATION 3

space between forms has been increased

channel of increased speed is longer and faster; in next iteration, see if slightly smaller opening between forms will still create the same type of channel

turbulent wind on the leeward side of the forms; in next iteration, make forms longer to see if they create calm leeward zones

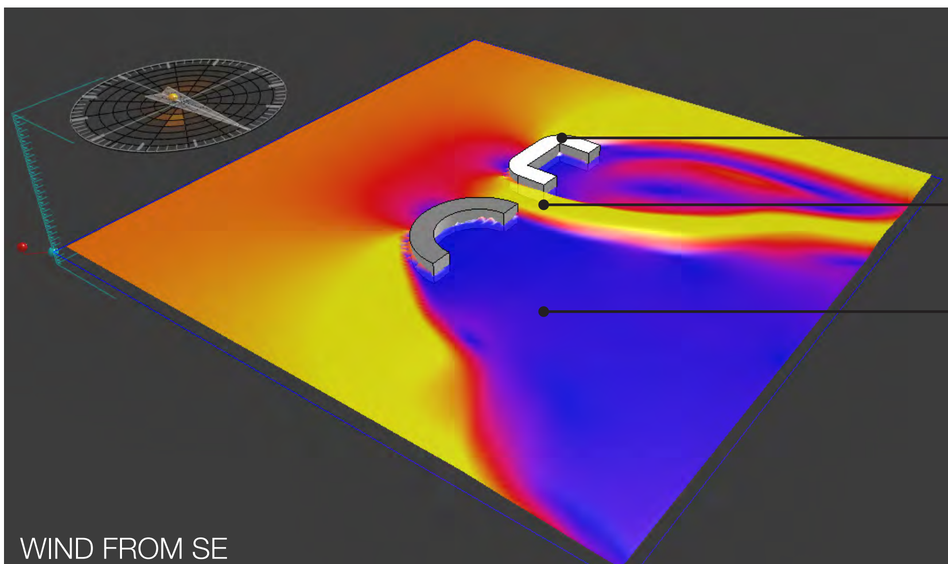


Fig. 3.73. Iteration 4 Vasari screenshot.

ITERATION 4

forms lengthened to create calm leeward zones

space between forms has been made smaller, but is still adequate to create a channel of increased wind speed

sheltered area on the leeward side; in next iteration, try to create a sheltered area on the windward side of the form for snow build-up

WIND SPEED

INCREASED

AVERAGE

DECREASED

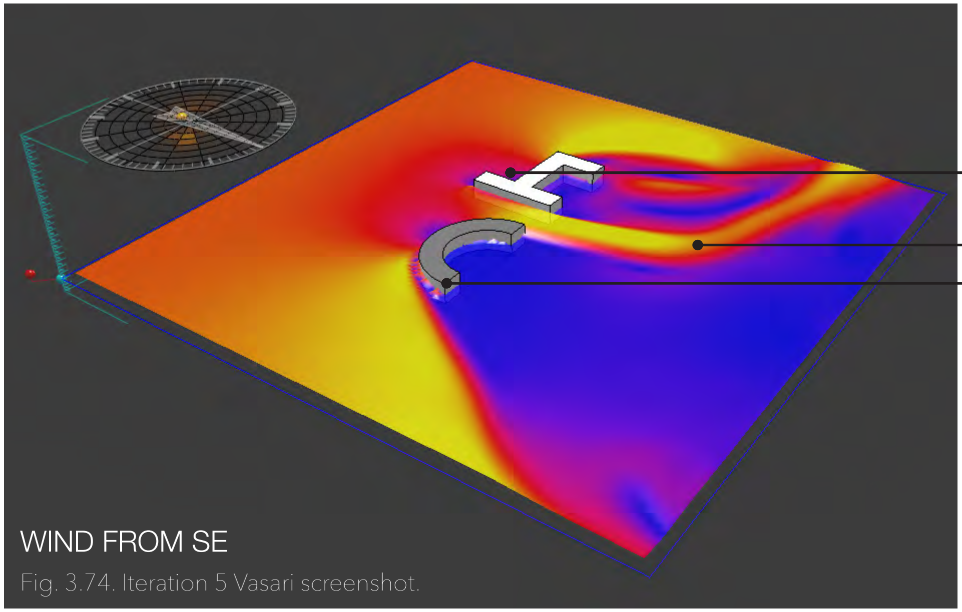


Fig. 3.74. Iteration 5 Vasari screenshot.

ITERATION 5

sheltered windward area isn't very large; in next iteration, create a porous wall for snow build-up on its leeward side instead

channel of increased wind speed curves into the zone of increased speed at the side of the forms

don't need this much building area; in next iteration replace some of the building form with walls

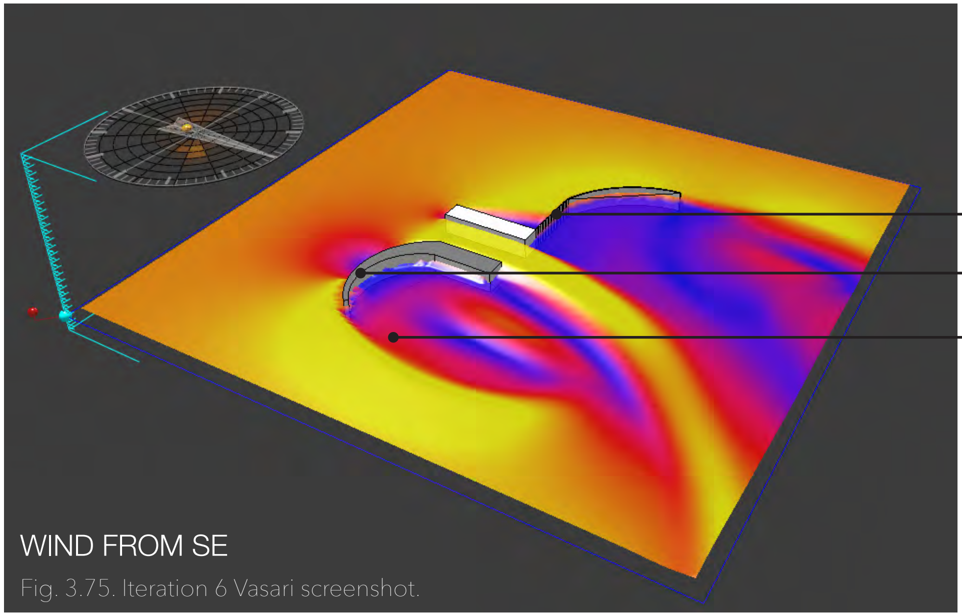


Fig. 3.75. Iteration 6 Vasari screenshot.

ITERATION 6

porous wall reduces wind speed and lets snow through for snow build-up on the leeward side

some building mass was changed to freestanding walls which decrease wind speed on the leeward side

this leeward zone isn't very sheltered; in next iteration, curve wall around more to shelter the zone from the wind

WIND SPEED


INCREASED

AVERAGE

DECREASED

WIND FROM ALL PREDOMINANT DIRECTIONS

The site on which this building form is developed has two predominant wind directions: northwest and southeast.[4] Since the wind comes from the southeast more often[5], the first six iterations of the building form have been designed to create certain wind conditions when the wind blows from only this direction. However, the northwest winds are nearly as predominant, so the next step in the design of the building form should be to adjust it so that the desired wind conditions for the exterior programs will be created by the form when the wind blows from either of these two directions. While this site has only two directions from which the wind blows most of the time, other sites may have more than two predominant wind directions that should be considered.

The sports programs are able to occur in different areas around the building depending on which direction the wind is coming from, as most of the required equipment is moveable. Although there is not a seasonal variation in the predominant wind direction on this particular site, if this method were to be applied to a site on which wind comes from one direction in the summer and a different direction in the winter, the seasonal sports programs could be arranged around the building based on the seasonality of the site's wind directions. On this site, however, all of the sports need to be accommodated when the wind blows from either direction, as the wind comes from the northwest and southeast in both the summer and winter.[6]

The wind energy generation technologies, unlike the sports programs, must remain stationary on the site. Because they are more limited, their optimal wind conditions are created when the wind comes from the southeast. When the wind comes from the northwest, the conditions that are created around each energy generation technology are either the same as the conditions from the southeast, or provide different conditions within which the technology may be tested. This provides an opportunity to study and compare the energy generation technologies within different wind conditions.

To adjust the building model to be able to create the desired wind conditions when the wind blows from either predominant direction, the model may be adjusted and tested in Vasari. For each iteration, the wind should be simulated from both directions to ensure that any changes to improve wind conditions when wind comes from the northwest do not negatively impact wind conditions when wind comes from the southeast. The wind speed that should be input is the average or highest speed for the specific wind direction being tested. The following five iterations were used to adjust the form of the building so that it is able to create the desired wind conditions from either predominant wind direction. The eleventh iteration accommodates all of the exterior programs in a wide variety of wind conditions. After this iteration, this step in the method was stopped and the resulting form was used to develop the next steps in the design methodology.

ITERATION 7

WALL ADDED AT NORTHWEST SIDE TO SHELTER SPACE FROM WIND FROM BOTH DIRECTIONS

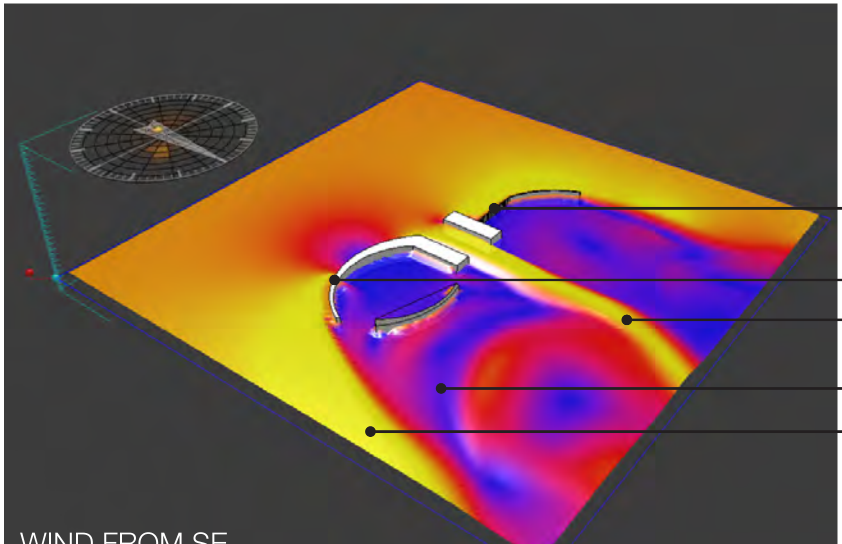


Fig. 3.76. Iteration 7 Vasari screenshot.

- wind is slowed by porous wall for snow build-up
- wall curved around more to better shelter the leeward area for tennis and badminton
- channel of increased wind speed for launch of kites, snowkites, and snow windsurfers
- large space with decreased wind speed for field sports
- zones of increased wind speed at the sides of the forms for snowkiting, snow windsurfing, and kite flying

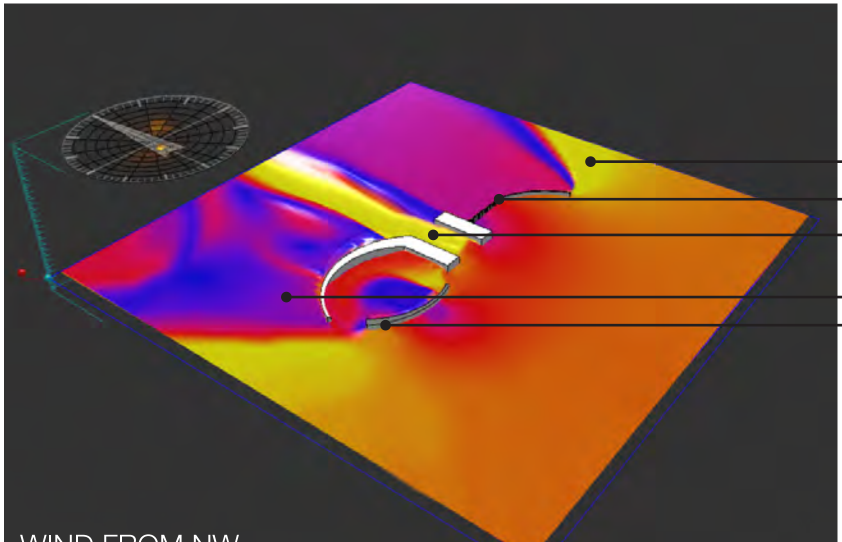


Fig. 3.77. Iteration 7 Vasari screenshot.

- zones of increased wind speed at the sides of the forms for snowkiting, snow windsurfing, and kite flying
- wind is slowed by porous wall for snow build-up
- channel of increased wind speed for launch of kites, snowkites, and snow windsurfers
- large space with decreased wind speed for field sports
- added wall shelters area for tennis and badminton from wind from either direction; in next iteration, curve this wall more to minimize wind in this area when wind comes from the NW

WIND SPEED

INCREASED

AVERAGE

DECREASED

ITERATION 8
FORMS ROTATED AND STAGGERED TO CREATE SIDEWAYS HIGH-SPEED WIND CHANNEL

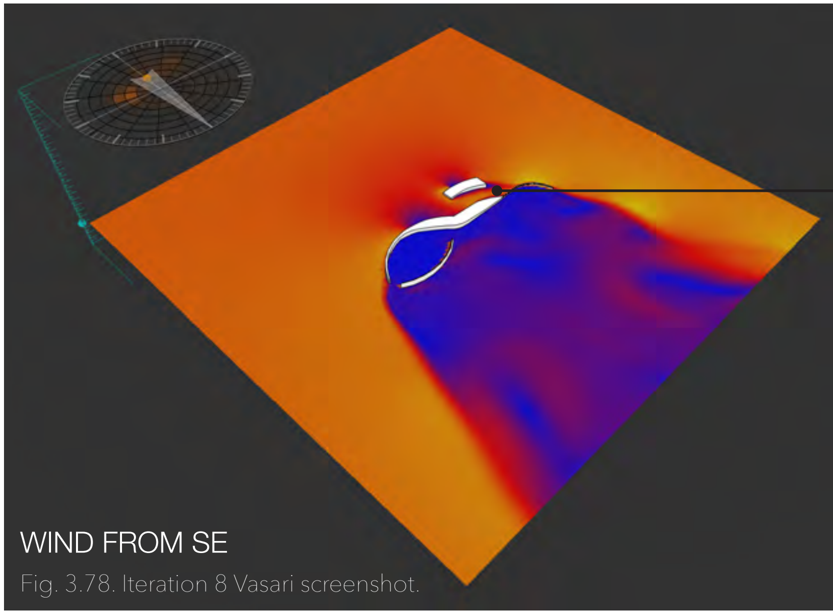

WIND FROM SE

Fig. 3.78. Iteration 8 Vasari screenshot.

placement of forms uses the staggering effect to direct the channel of increased wind speed into the high-speed area at the side

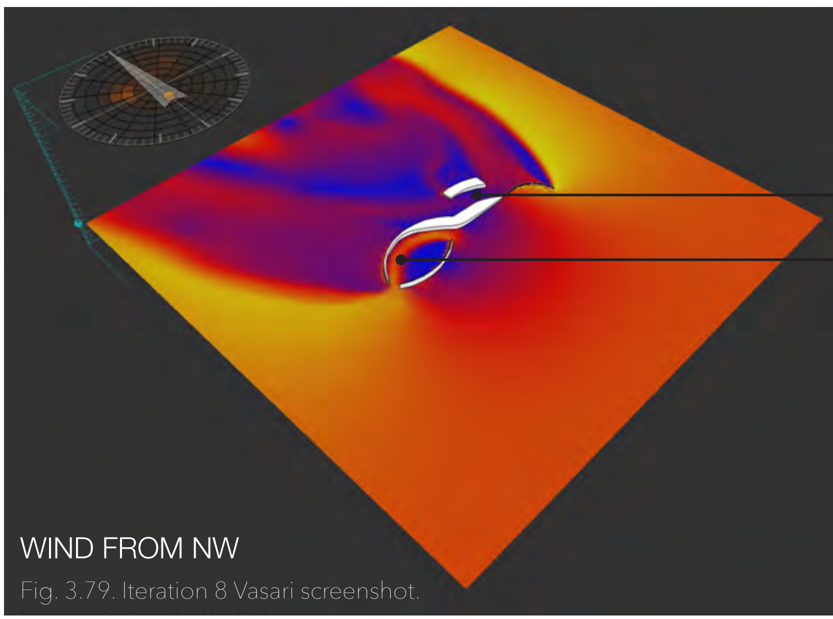

WIND FROM NW

Fig. 3.79. Iteration 8 Vasari screenshot.

no channel of high-speed wind is created when wind comes from the NW; in next iteration, add a wall to create a high-speed wind stream with NW wind

wall was curved more to reduce wind in this area, but a high-speed wind stream enters the courtyard when wind comes from the NW; fix this in a subsequent iteration

WIND SPEED

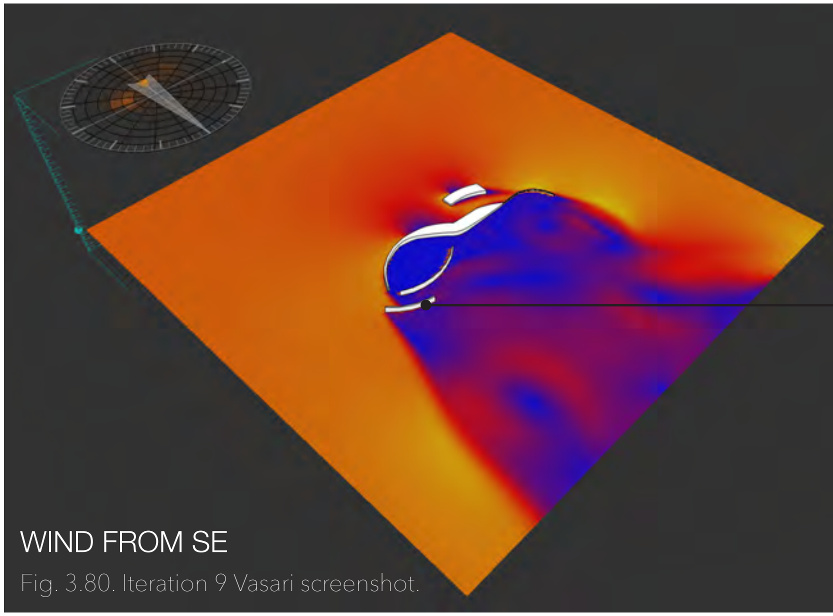
INCREASED

AVERAGE

DECREASED

ITERATION 9

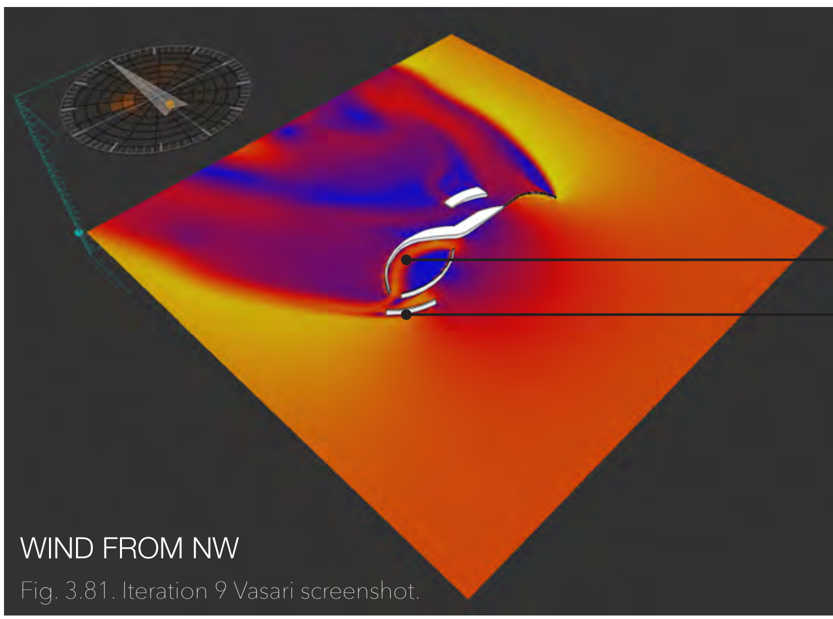
WALL ADDED AT NORTH END OF FORM TO CREATE HIGH-SPEED WIND CHANNEL WITH WIND FROM THE NW



WIND FROM SE

Fig. 3.80. Iteration 9 Vasari screenshot.

added wall does not negatively impact wind conditions when wind comes from the SE



WIND FROM NW

Fig. 3.81. Iteration 9 Vasari screenshot.

stream of increased wind speed comes into sheltered area when wind blows from the NW; in next iteration, adjust form so that this does not happen

wall added to create high-speed wind channel when wind blows from the NW, to mirror the high-speed wind channel on the other side of the building when wind comes from the SE

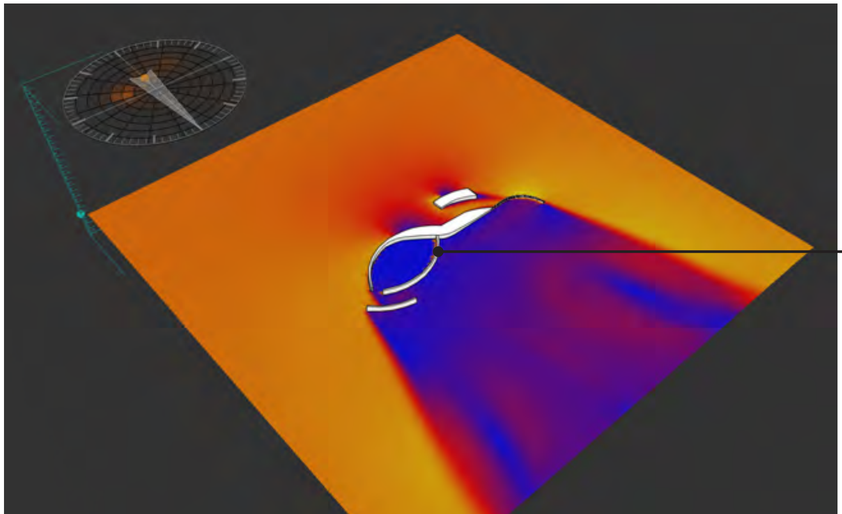
WIND SPEED

INCREASED

AVERAGE

DECREASED

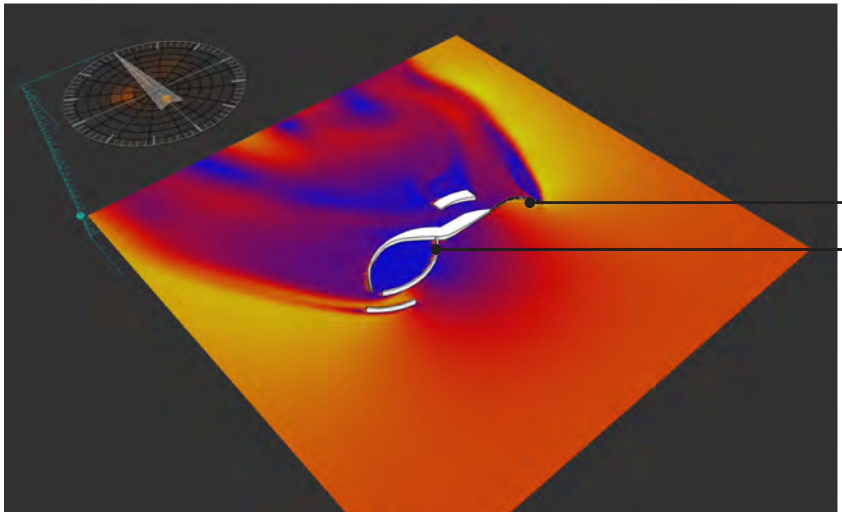
ITERATION 10
WALL CURVED TO SHELTER COURTYARD FROM NW WINDS



WIND FROM SE

Fig. 3.82. Iteration 10 Vasari screenshot.

curved wall does not impact wind conditions when wind blows from the SE



WIND FROM NW

Fig. 3.83. Iteration 10 Vasari screenshot.

curved wall doesn't alter wind conditions when wind blows from the NW; in next iteration, replace with a straight, porous wall to see if the curved wall is needed

wall is curved more to shelter the courtyard from the stream of high-speed wind that was entering the courtyard during winds from the NW

WIND SPEED

INCREASED

AVERAGE

DECREASED

ITERATION 11

CURVED WALL AT SOUTH END REPLACED WITH STRAIGHT, POROUS WALL

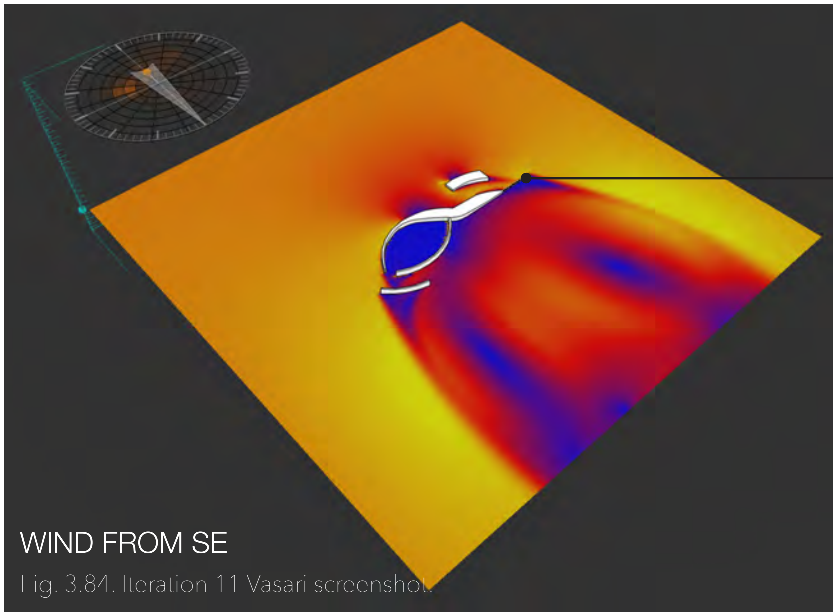


Fig. 3.84. Iteration 11 Vasari screenshot.

straight, porous wall does not negatively alter wind conditions when wind blows from the SE

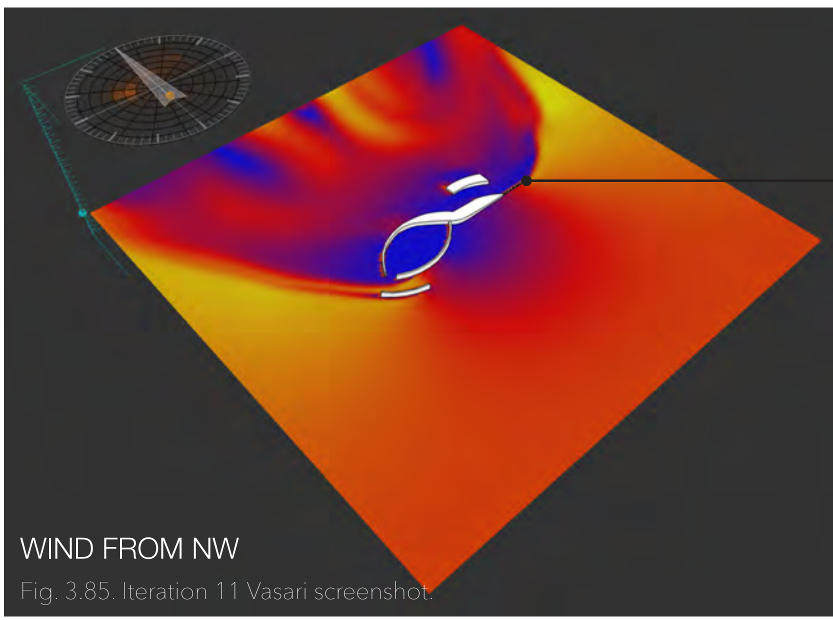


Fig. 3.85. Iteration 11 Vasari screenshot.

straight, porous wall does not negatively alter wind conditions when wind blows from the NW

WIND SPEED
INCREASED
AVERAGE
DECREASED

ITERATION 11 | WIND FROM SE

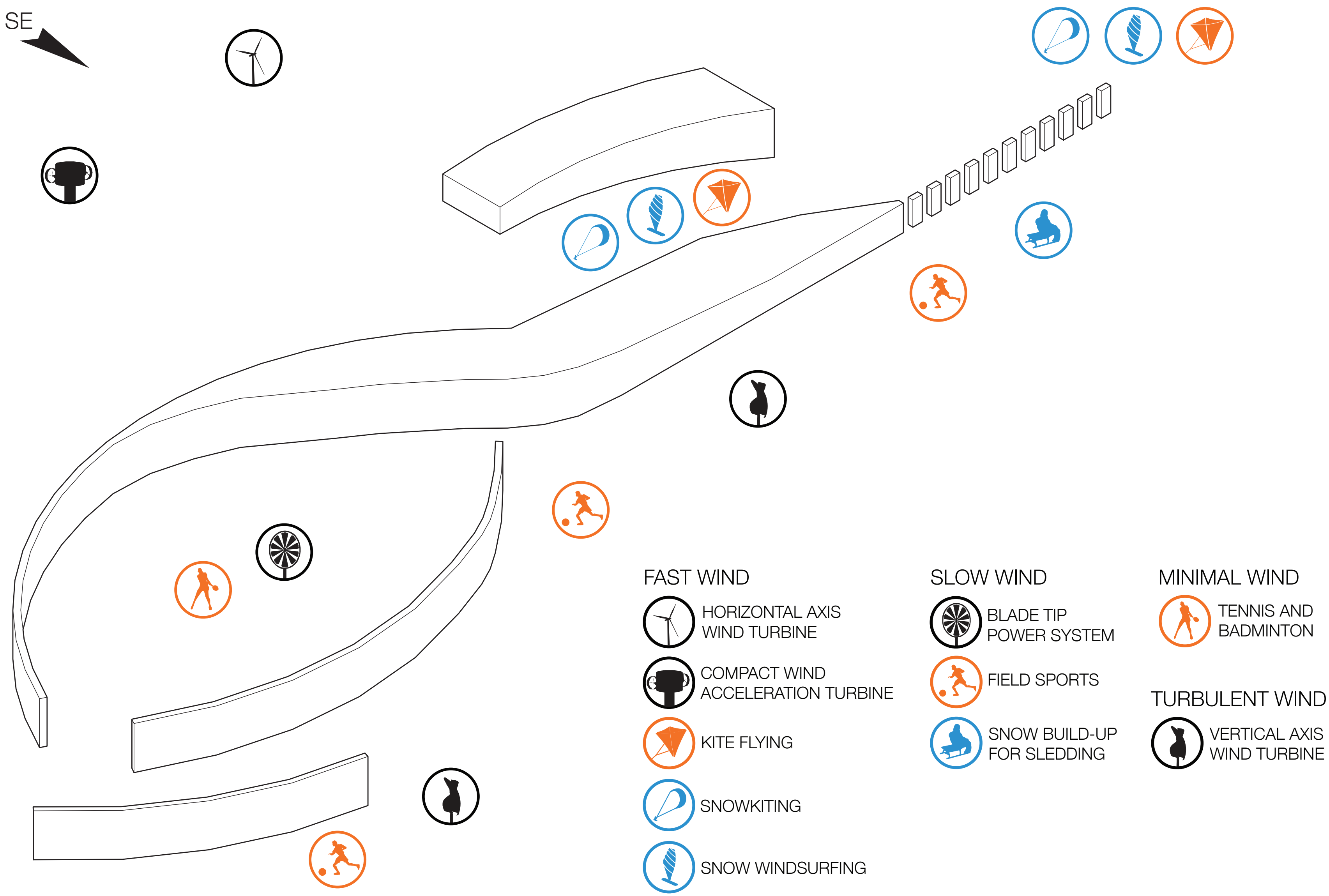


Fig. 3.86. Form with exterior programs.

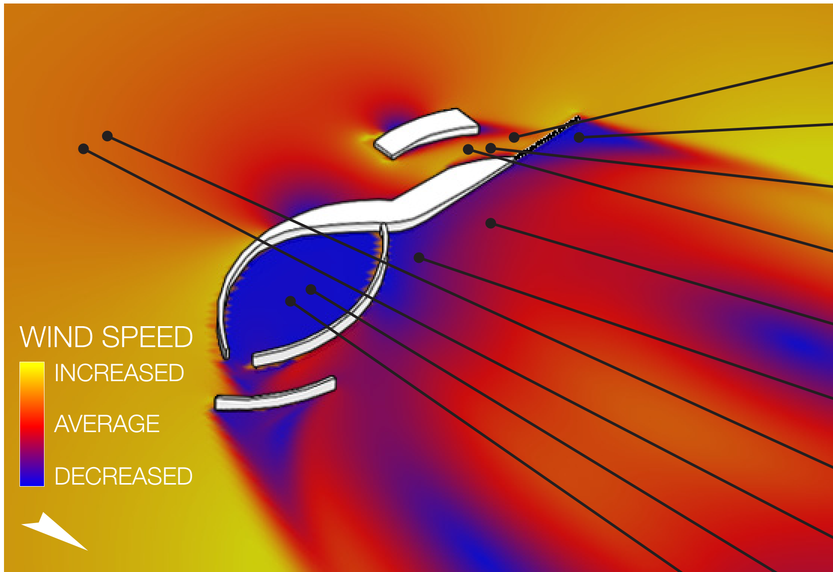


Fig. 3.87. Wind speed from Vasari.

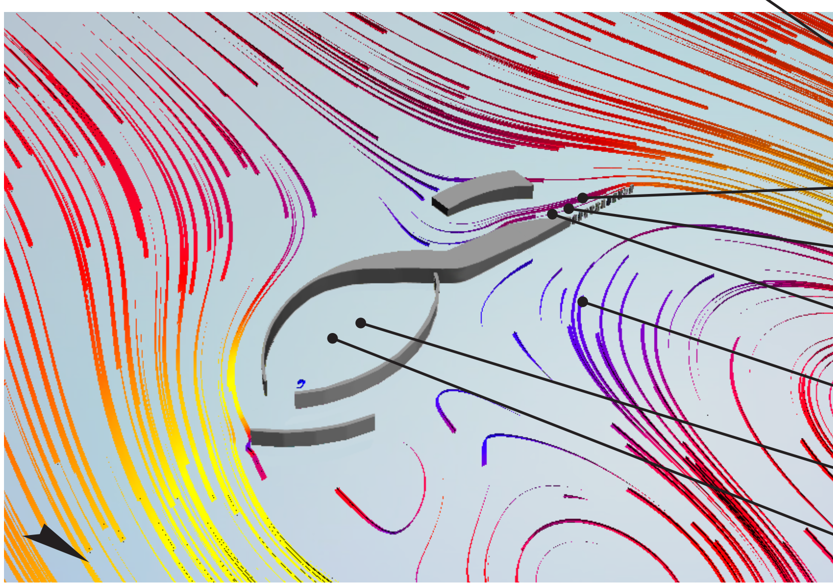


Fig. 3.88. Flow lines from Flow Design.

ITERATION 11 | WIND FROM SE | SUMMER

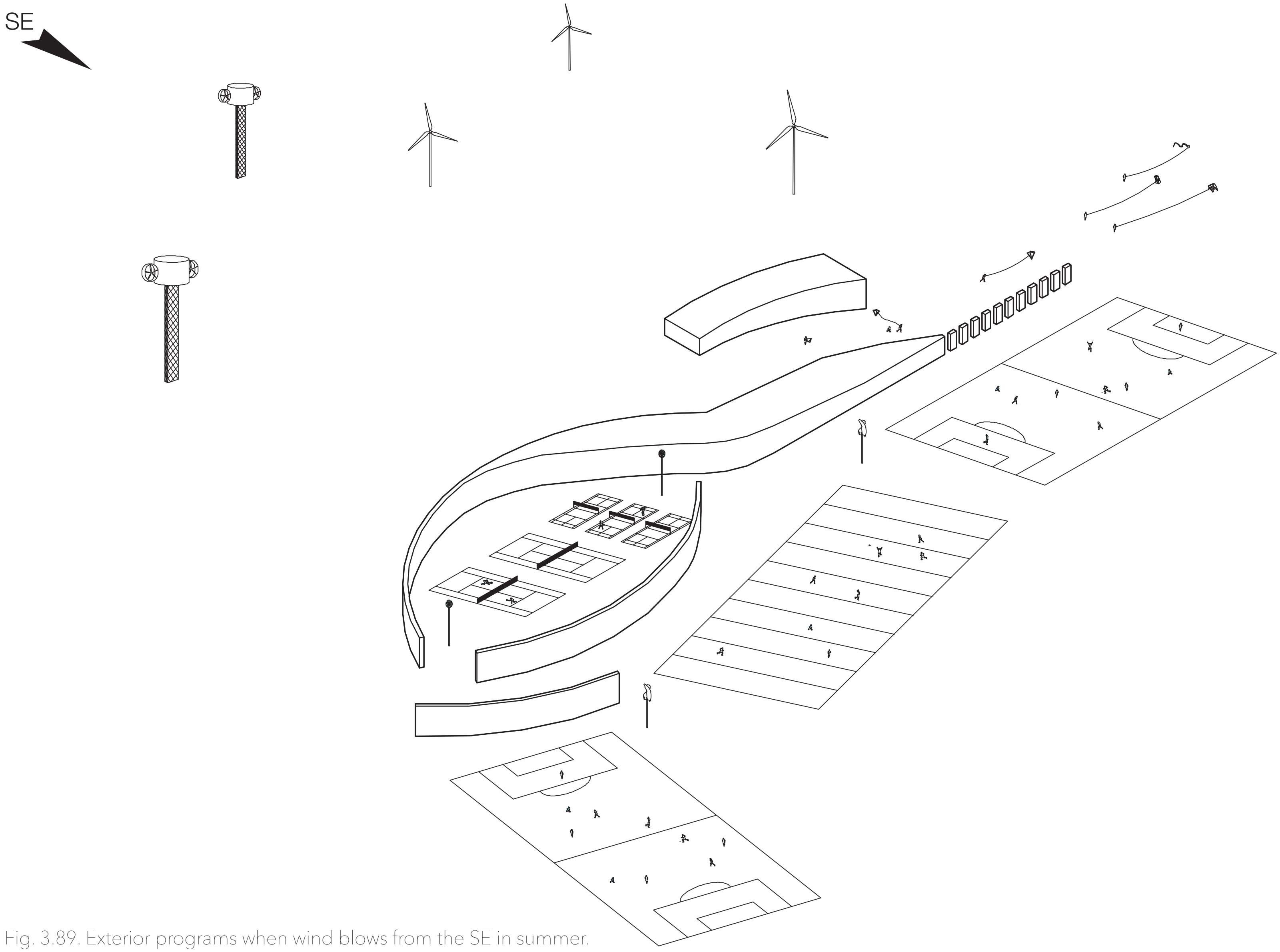


Fig. 3.89. Exterior programs when wind blows from the SE in summer.

ITERATION 11 | WIND FROM SE | WINTER

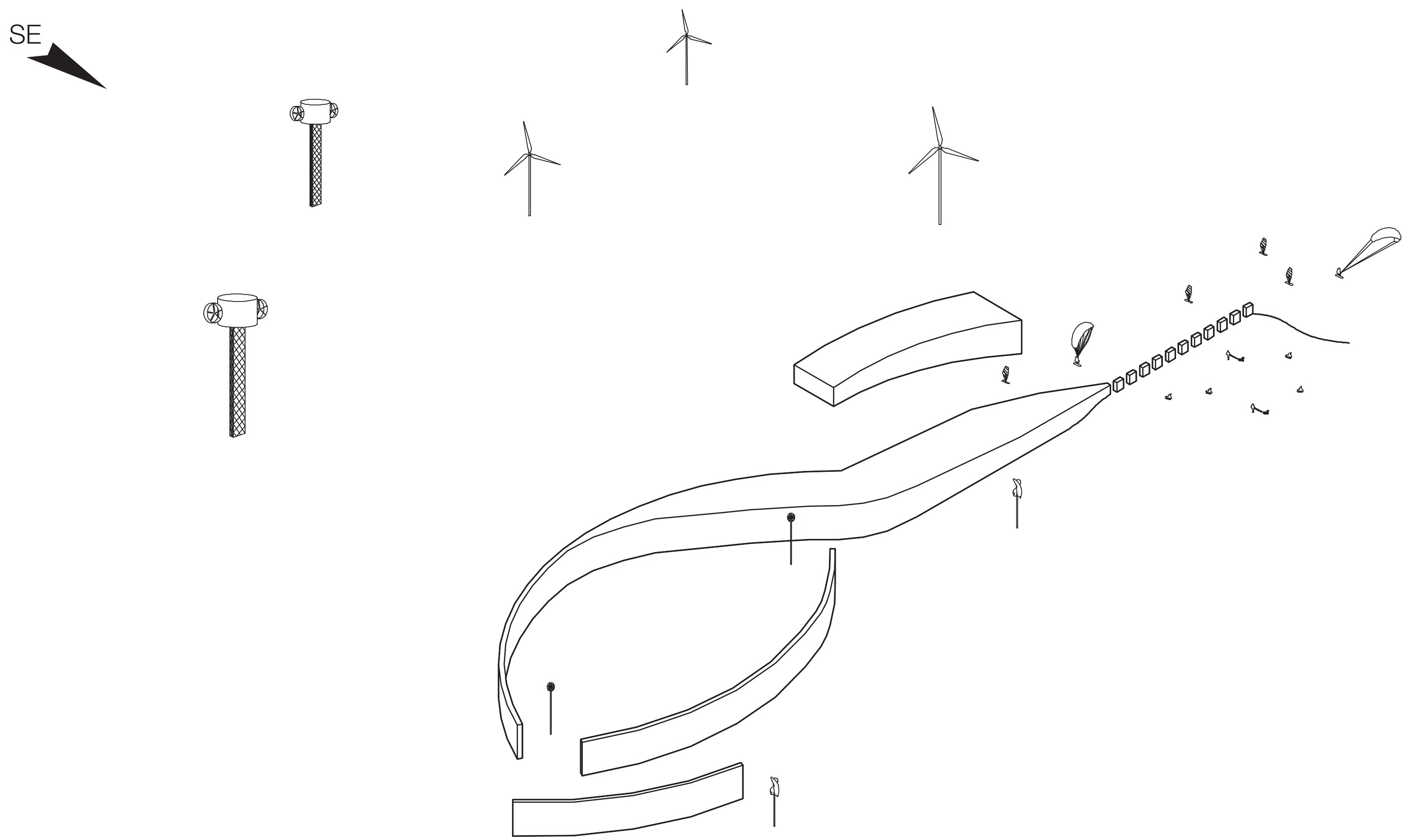


Fig. 3.90. Exterior programs when wind blows from the SE in winter.

ITERATION 11 | WIND FROM NW

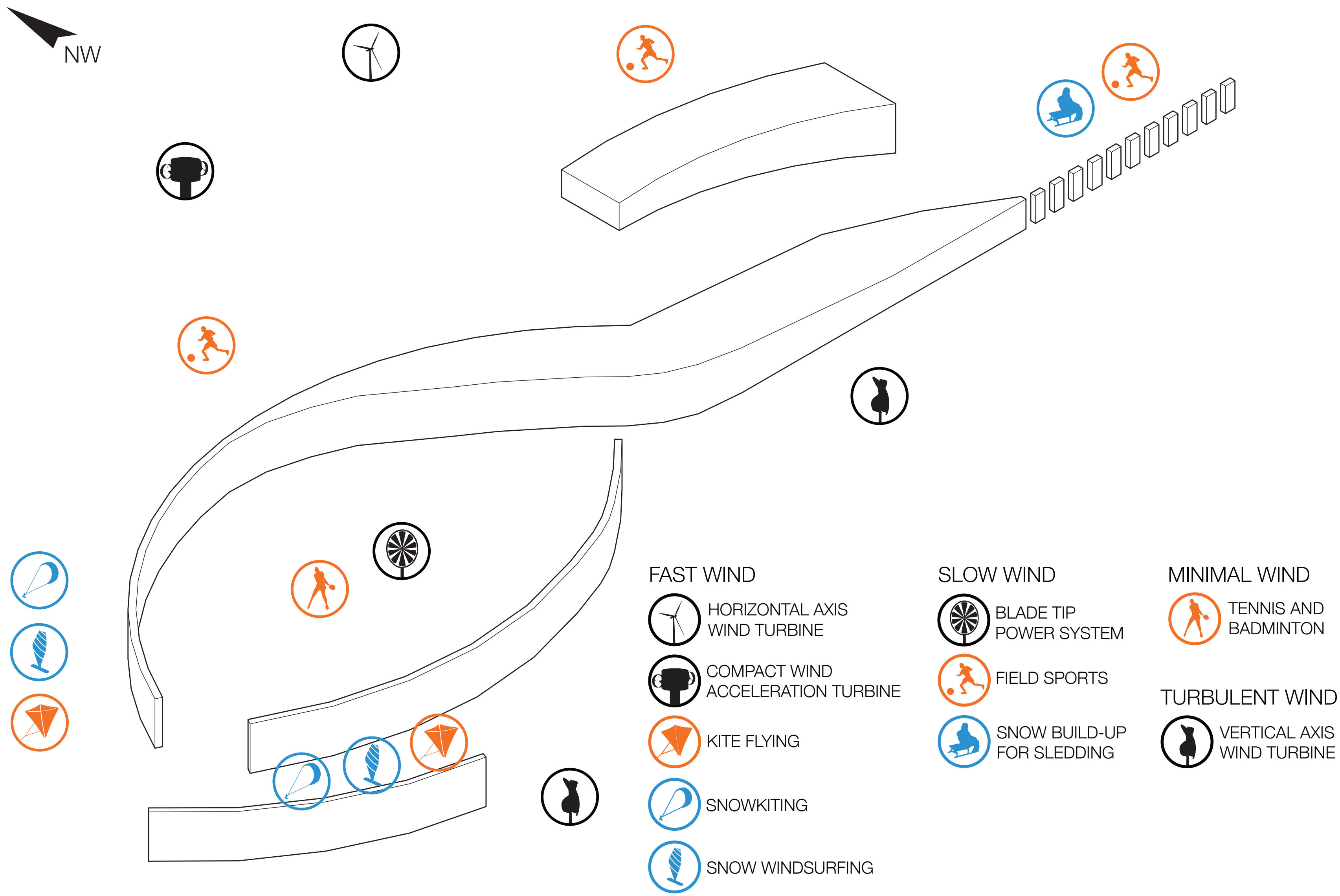


Fig. 3.91. Form with exterior programs.

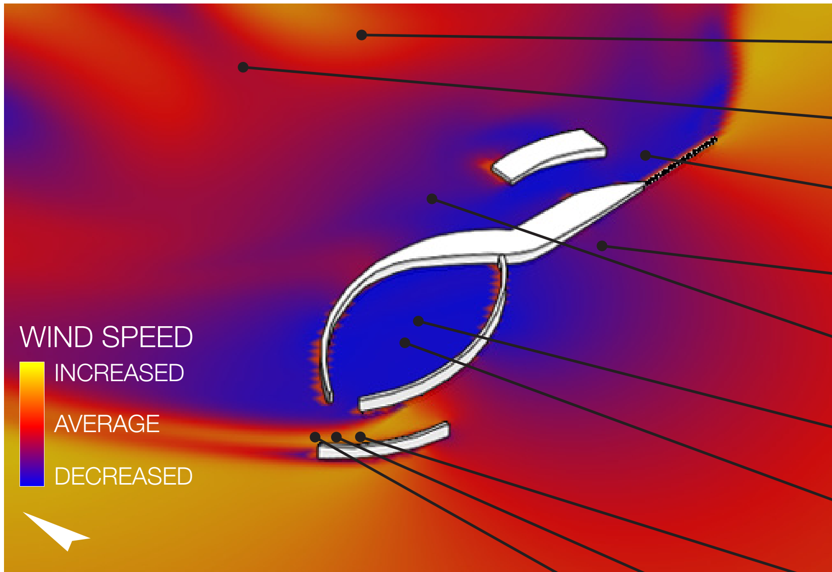


Fig. 3.92. Wind speed from Vasari.

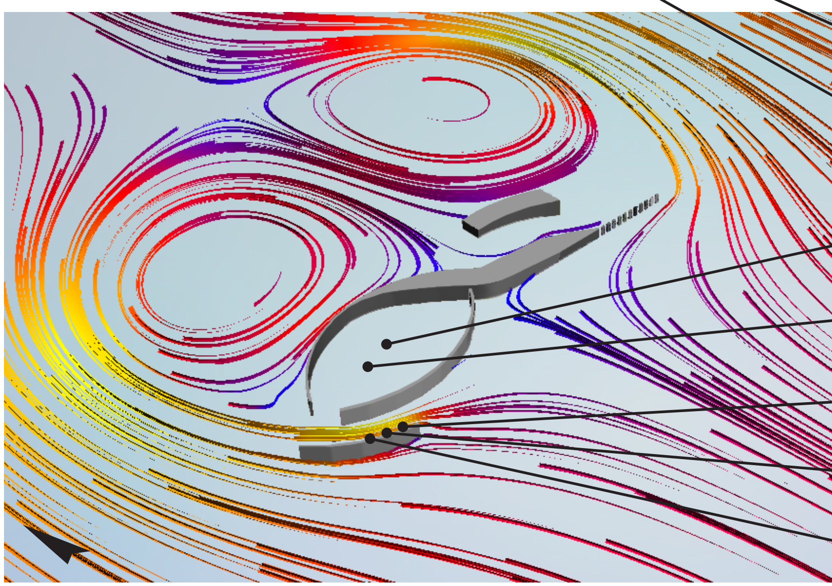


Fig. 3.93. Flow lines from Flow Design.

ITERATION 11 | WIND FROM NW | SUMMER

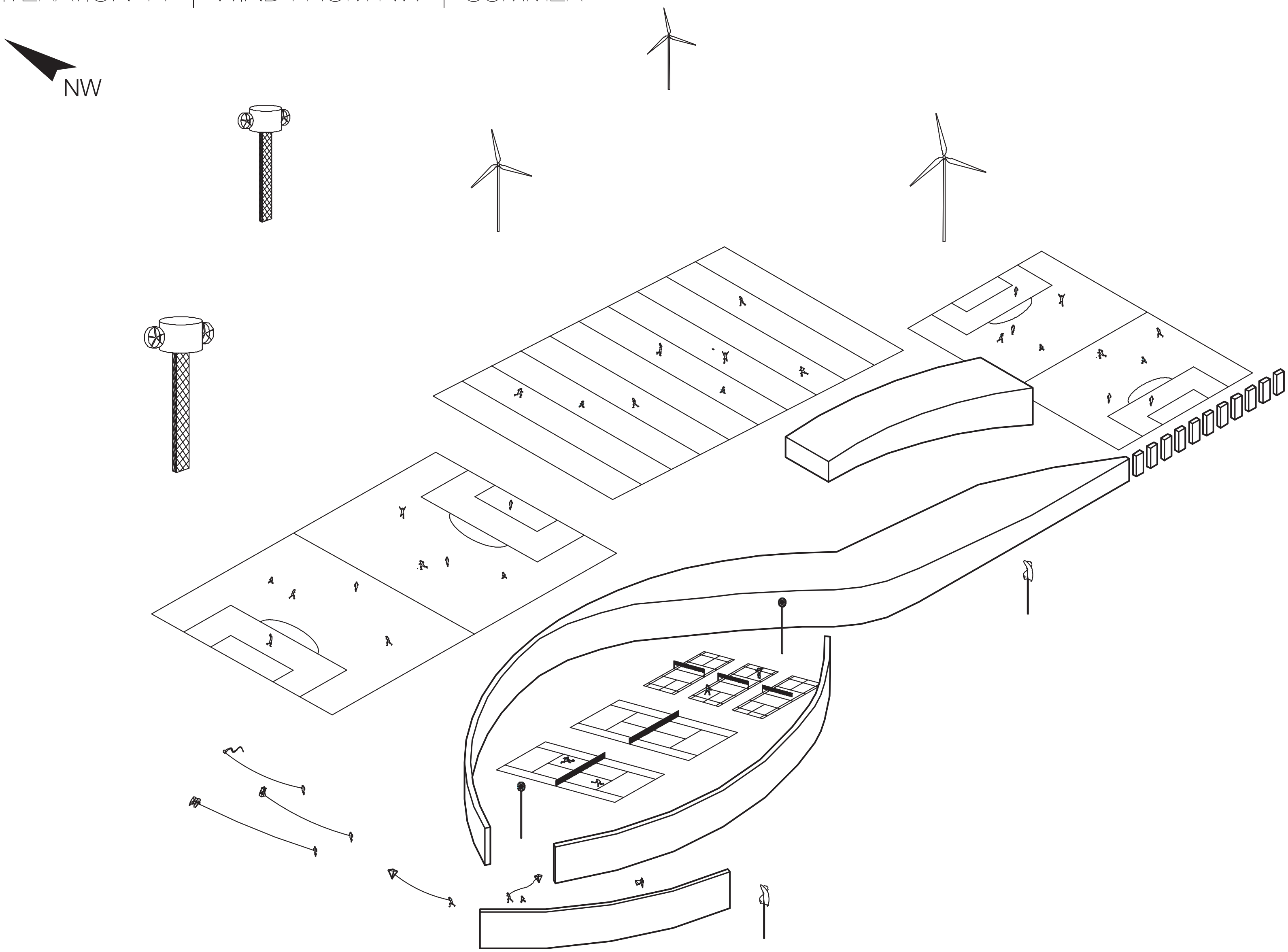


Fig. 3.94. Exterior programs when wind blows from the NW in summer.

ITERATION 11 | WIND FROM NW | WINTER

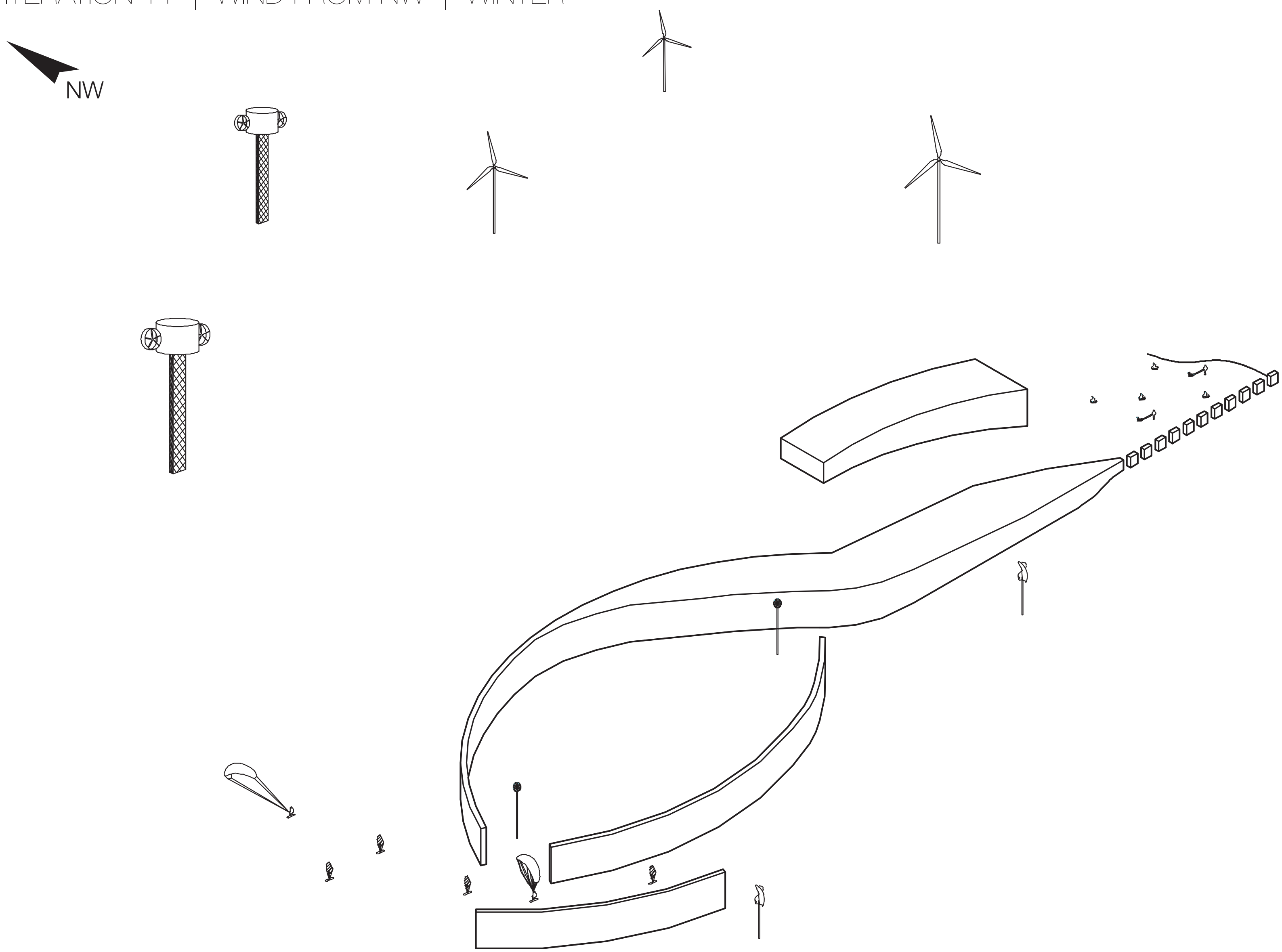


Fig. 3.95. Exterior programs when wind blows from the NW in winter.

WIND AFFECTS FORM

HOW WIND AFFECTS FORM

When a building obstructs wind flow, the wind exerts pressure on the building.[1] In general, wind pressure acts perpendicular to the surface on which it is exerted.[2] Positive wind pressure pushes the **windward** building walls inwards (Fig. 4.1).[3] Along the leading edges of the building that are exposed to the oncoming wind, the wind flow increases in velocity and detaches from the building surface.[4] This creates zones of negative pressure along the **leeward** building faces and the streamwise building faces, which include the roof and walls that are parallel to the direction of the wind flow (Fig. 4.1).[5] This negative pressure pulls these building faces outwards.[6] Within a courtyard, positive pressure is exerted on the wall facing the oncoming wind, and negative pressure is exerted on the wall facing away from the direction of the wind (Fig. 4.1).[7]

The shape of a building can affect the amount of wind pressure, and the resultant wind force, that acts on its faces.[8] While this wind pressure cannot be completely eliminated, there are ways that buildings may be formed to reduce the pressure and overall wind force that is exerted on them.

The second step in the design method is carried out concurrently with the step that was outlined in the previous chapter, in which the building form is designed to create particular surrounding wind conditions. For each building design iteration, CFD software is used to evaluate the **aerodynamics** of the building form by providing information about the wind pressure that is exerted on each building face. The speed with which these results are provided allows the architect to refine and re-test many iterations of their design until the building form has the desired **aerodynamic** properties.

Windward
(adj.) The side of an obstruction that is facing the wind.
(adv.) On the side of an obstruction that is facing the wind.

Leeward
(adj.) The side of an obstruction that is sheltered from the wind.
(adv.) On the side of an obstruction that is sheltered from the wind.

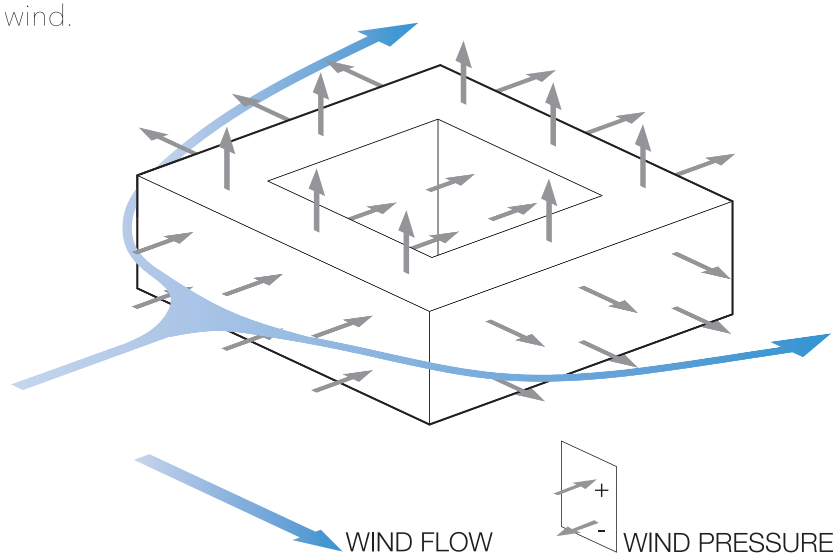


Fig. 4.1. Wind pressure distribution over a building.

Aerodynamics
The study of the interaction between solid forms and air when at least one of them is in motion, not necessarily referring to solid forms that are shaped to reduce drag caused by surrounding wind.

Aerodynamic
The quality of a form to have a shape that reduces drag caused by surrounding wind.

AERODYNAMIC FORMS LIBRARY

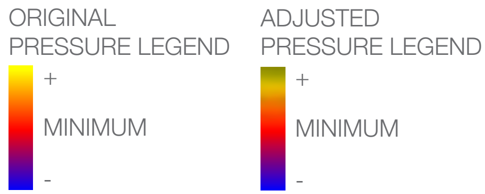
The following library of aerodynamic forms shows how forms can be designed to increase or decrease the wind pressure or overall wind force that is exerted over them. These forms were studied and compiled from a variety of published sources.[9] This library may be referred to while designing and adjusting the initial building form to reduce the amount of wind pressure or force acting on it. For each factor, the studied effect is compared with the Flow Design simulation of the wind pressure over the form. The Flow Design pressure simulations allow the architect to become familiar with how accurately the software represents surface pressure variations, so that they will be able to tell if the simulated wind pressure over their building design iterations is an accurate representation of the ways in which the building form would affect the wind pressure acting on it.

It should be noted that because this thesis focuses on the design of a low-rise building, the ways in which building height and aspect ratio affect wind pressure are not considered.

ORIENTATION

SURFACE ORIENTATION IN RELATION TO WIND DIRECTION AFFECTS PRESSURE DISTRIBUTION

It should be noted that the colour gradients representing pressure from Flow Design do not always match the colours of the original legend from Flow Design (left), so an adjusted legend (right) may also be used to interpret the pressure distribution screenshots.



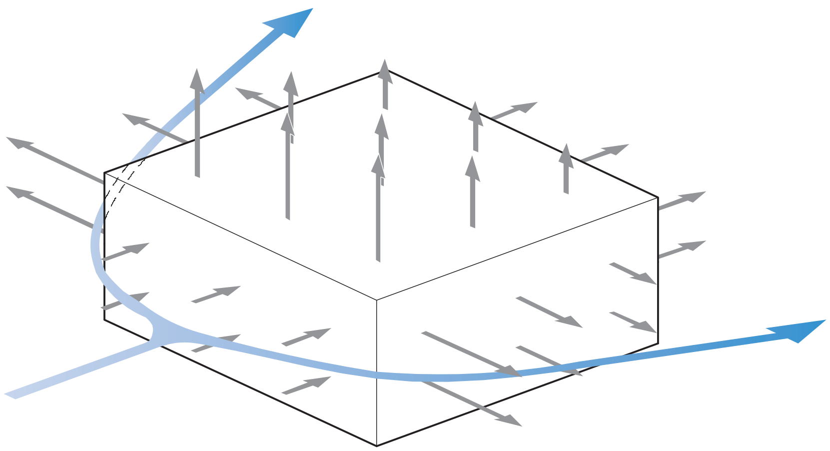


Fig. 4.2. Effect of orientation on wind pressure.

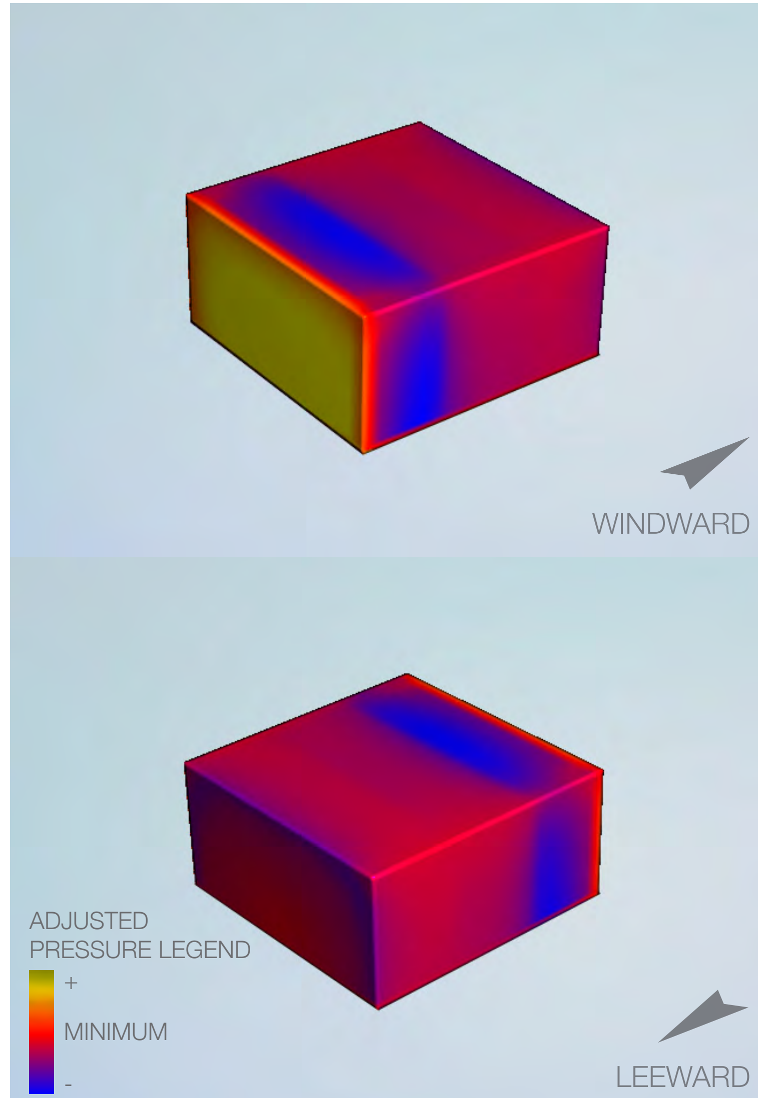


Fig. 4.3. Flow Design simulation.

WIND SPEED

SLOWER SPEED DECREASES PRESSURE

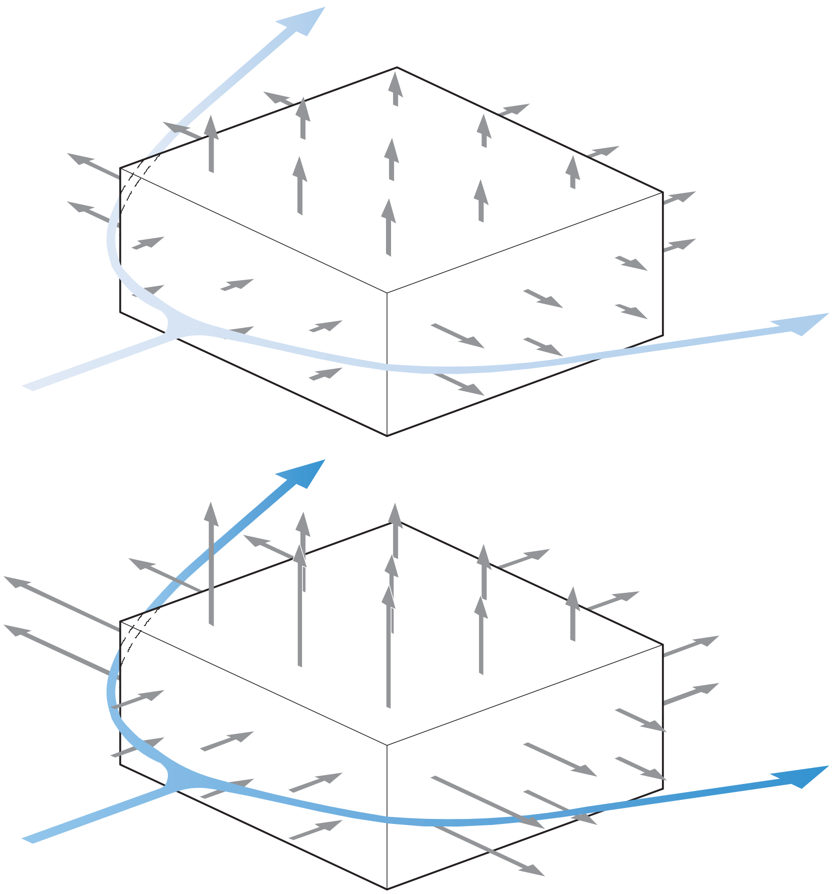


Fig. 4.4. Effect of wind speed on wind pressure.

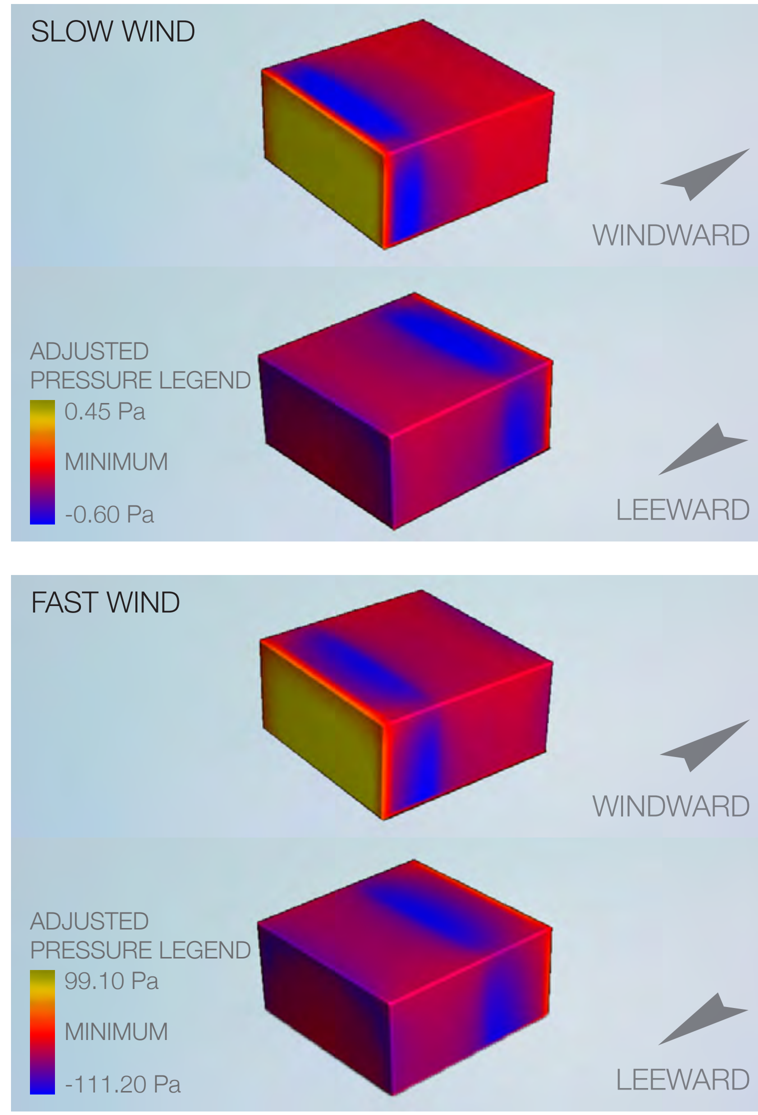


Fig. 4.5. Flow Design simulation.

FORM

STREAMLINED FORM DECREASES OVERALL WIND FORCE

It should be noted that although these form manipulations reduce the overall wind force acting on it, they may not necessarily reduce the wind pressure on localized areas of the surface.[10]

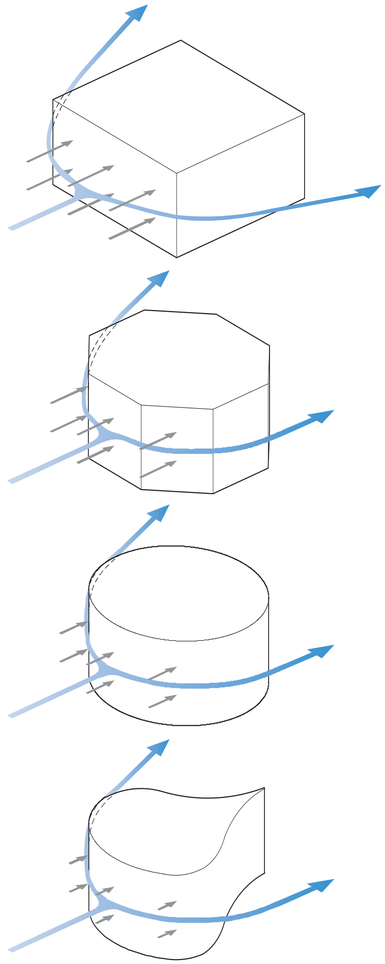


Fig. 4.6. Effect of form on wind force.

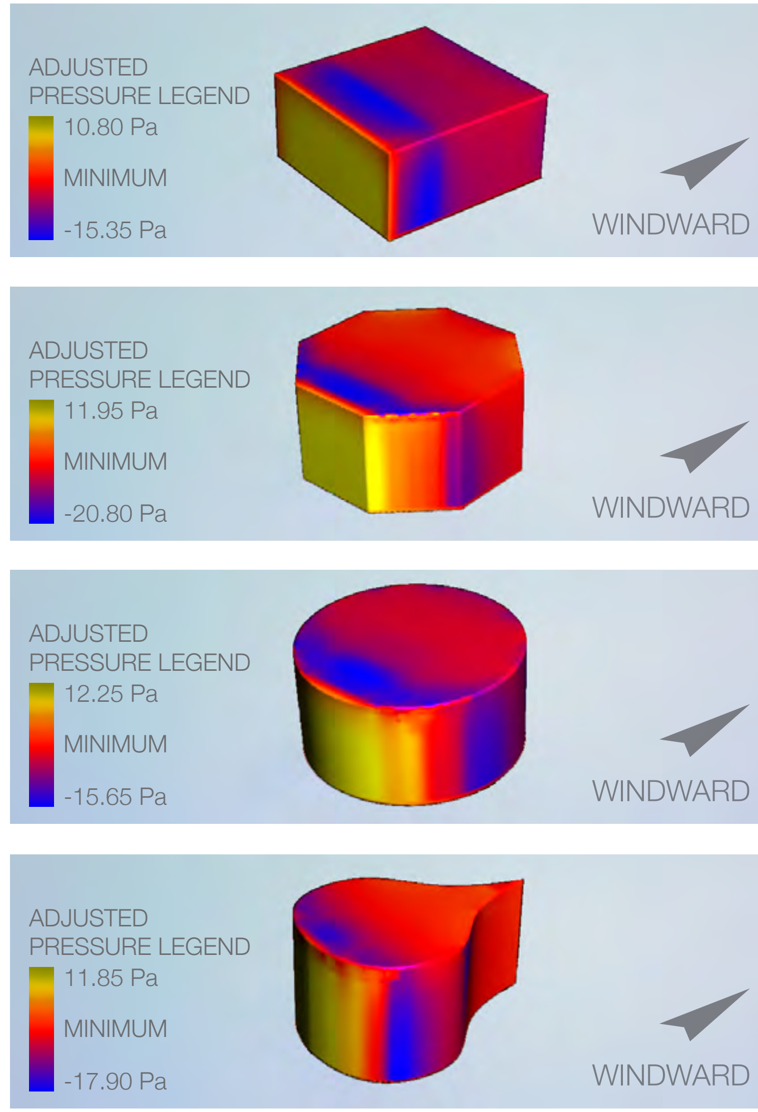


Fig. 4.7. Flow Design simulation - effect not shown.

EXPOSURE

UPWIND OBSTRUCTIONS DECREASE WIND FORCE

It should be noted that although these upwind obstructions generally decrease the overall wind force that is exerted on the downwind form, they may increase the wind pressure on localized areas of the downwind form's windward surface.[11]

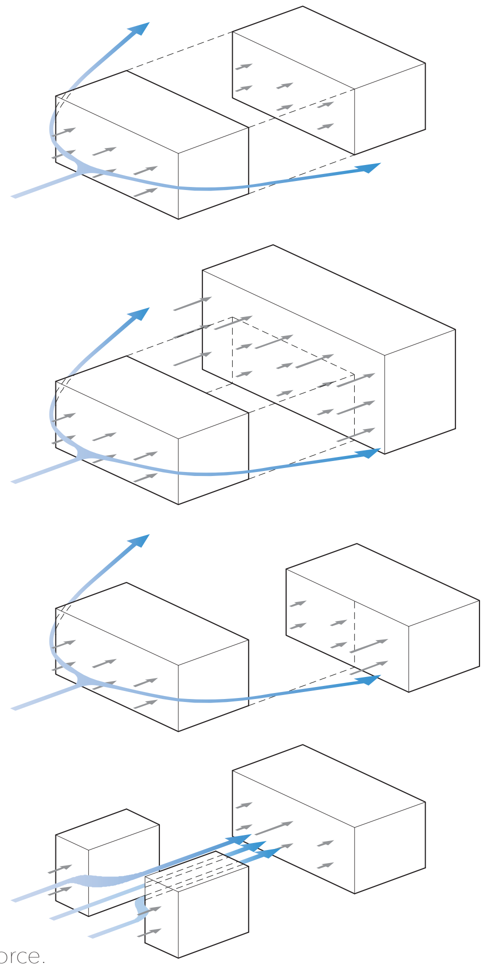


Fig. 4.8. Effect of exposure on wind force.

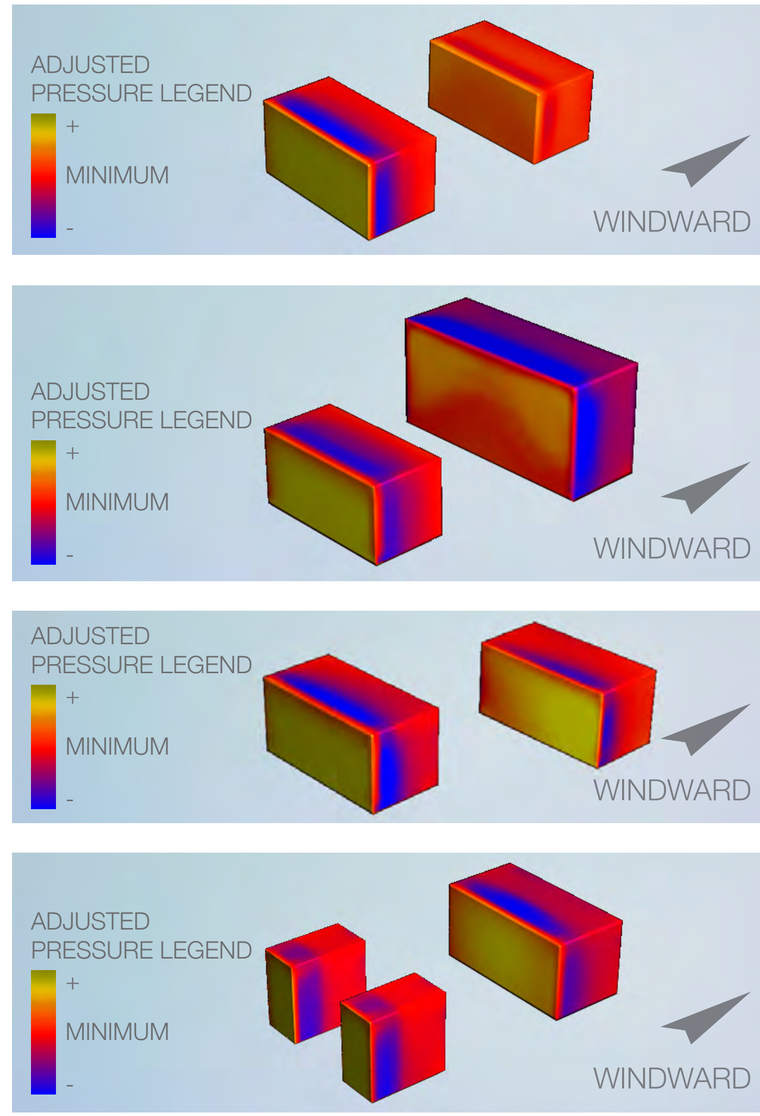


Fig. 4.9. Flow Design simulation.

POROSITY

HIGHER POROSITY DECREASES WIND FORCE ON LEEWARD FACE

It should be noted that although a higher porosity reduces the overall wind force on the form by reducing the suction on the leeward face, it may not necessarily reduce the wind pressure on some localized areas of the surface.[12]

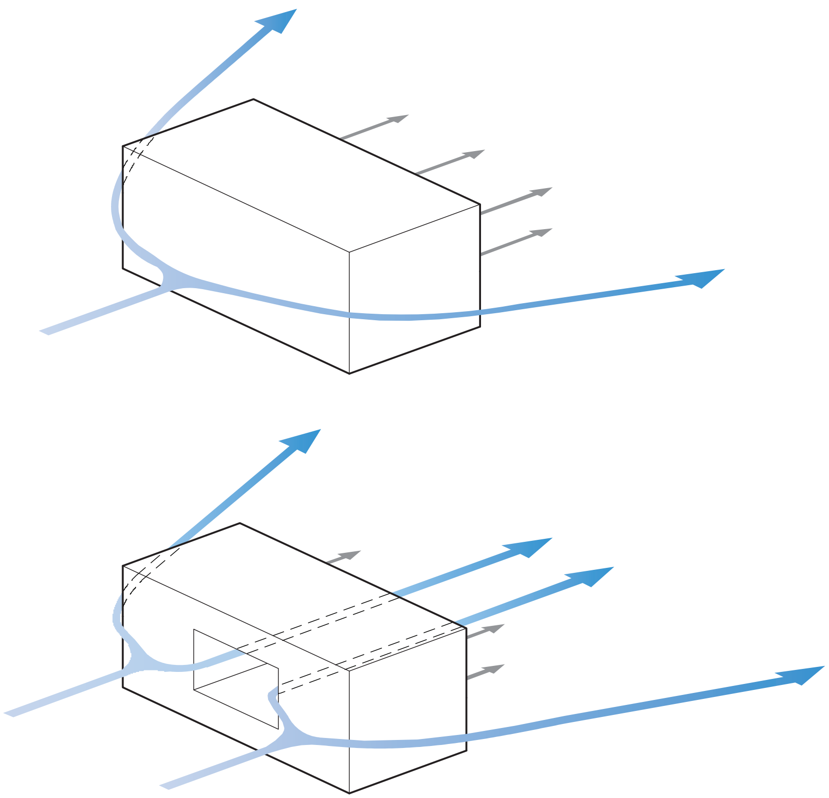


Fig. 4.10. Effect of porosity on wind force.

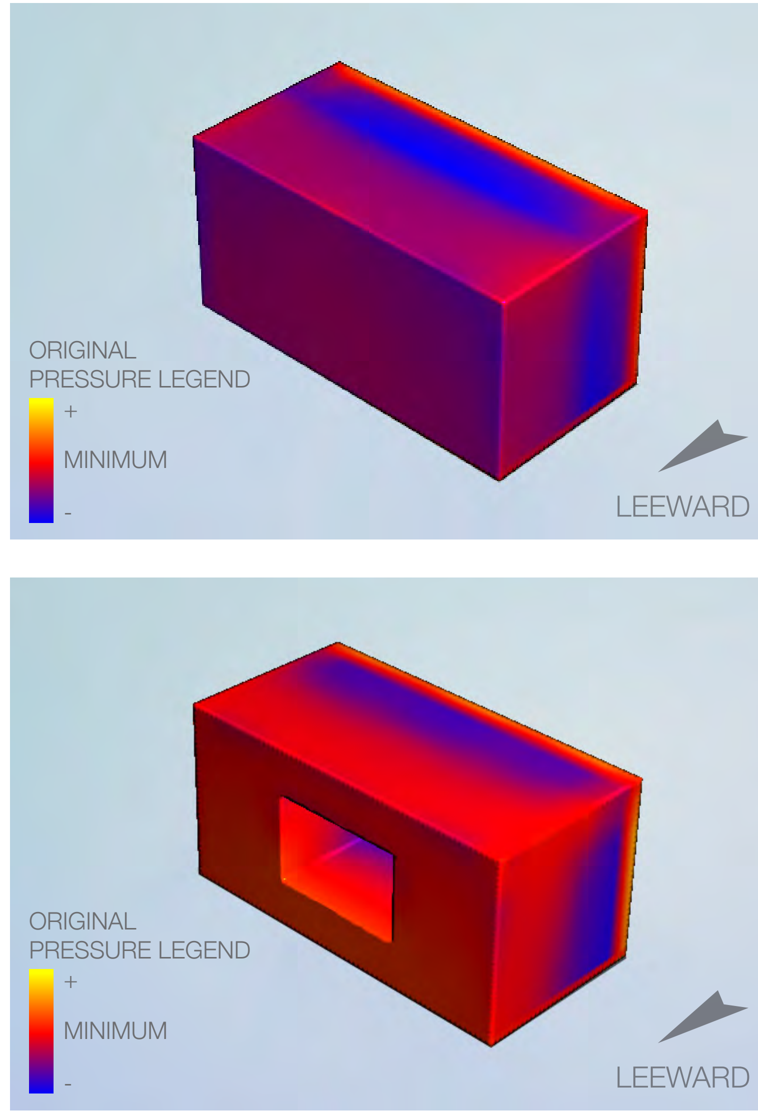


Fig. 4.11. Flow Design simulation.

CFD ITERATIONS TO IMPROVE FORM AERODYNAMICS

For the next step in the design method, CFD software is used to evaluate the aerodynamics of the building form by depicting how much wind pressure is exerted over the model's surface. The amount of wind pressure that acts across the surface is represented by colour gradients in Flow Design. After each iteration is tested within the simulated wind conditions, the designer makes observations and adjusts the form for the next iteration to improve the form's aerodynamics. These adjustments to the form may be designed by referring to the aerodynamic forms library, which catalogues ways of manipulating the form to decrease the wind pressure or force acting on it. These observations and adjustments are done concurrently with the adjustments to improve the surrounding wind conditions that were described in the previous chapter, and as such, the forms of each iteration in this chapter are the same as those in the previous chapter.

The eleven iterations were developed to improve the aerodynamics of the building form, looking at the wind pressure on both the windward and leeward building faces. Like the previous chapter, the first six iterations evaluate the wind pressure acting on the building when the wind comes only from the most predominant southeast direction, and iterations 7-11 consider wind pressure when wind comes from both of the site's predominant wind directions. These simulations of wind pressure from multiple directions ensure that the building form is aerodynamically designed to reduce the wind pressure acting on it within all of the site's frequently-occurring wind conditions.

It should be noted that Flow Design shades some faces of the forms, rendering them black. The user of the software may rotate the form to bring the shaded faces into the light to see the wind pressure distribution over them.

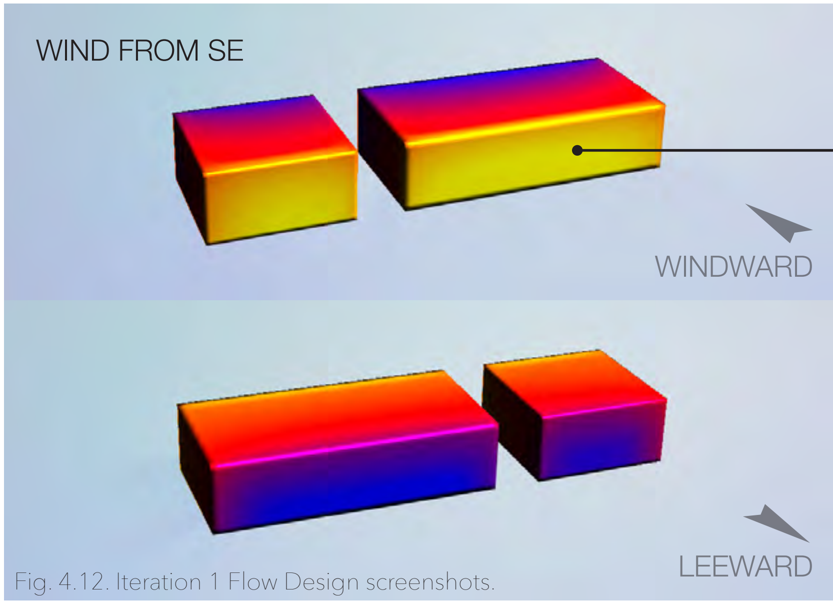


Fig. 4.12. Iteration 1 Flow Design screenshots.

ITERATION 1

simple forms are tested for the first iteration only to manipulate wind patterns, not considering aerodynamics at this point

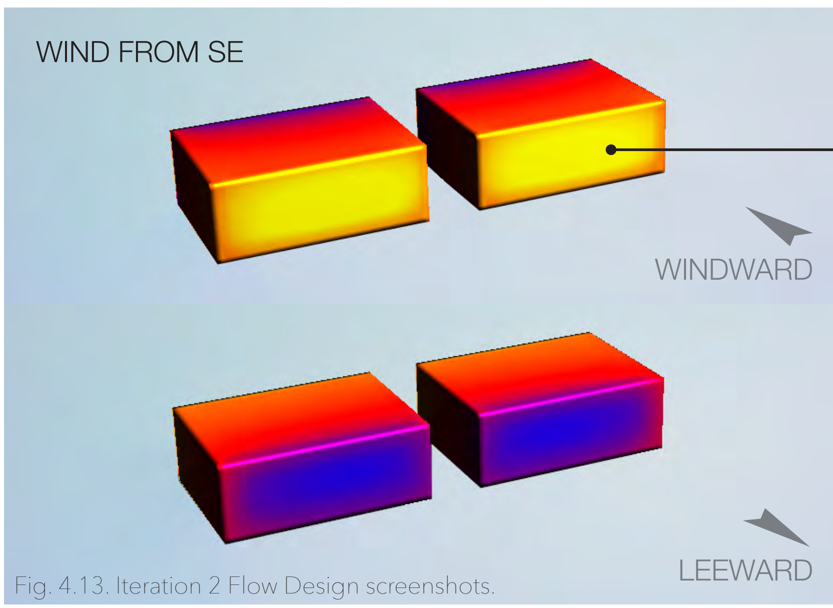
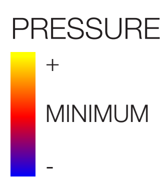


Fig. 4.13. Iteration 2 Flow Design screenshots.

ITERATION 2

blunt, simple forms are still used in the second iteration, which was altered only to change the wind patterns around the forms



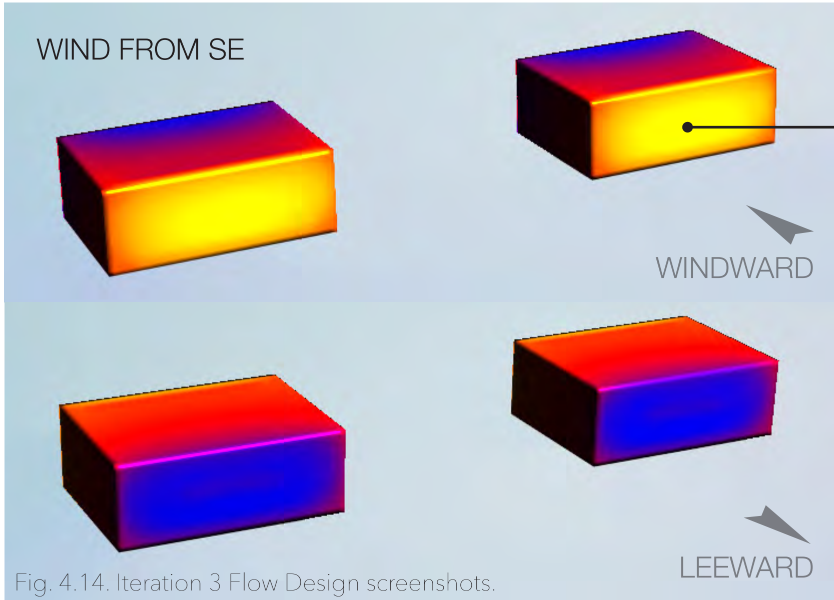


Fig. 4.14. Iteration 3 Flow Design screenshots.

ITERATION 3

blunt, simple forms are still used in the third iteration, which was altered only to change the wind patterns around the forms

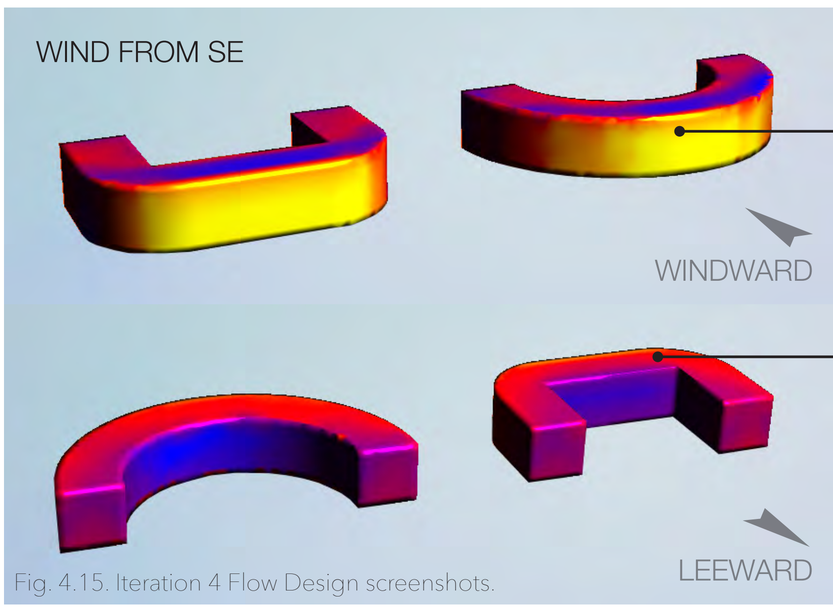
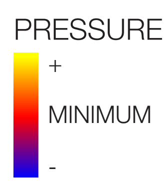


Fig. 4.15. Iteration 4 Flow Design screenshots.

ITERATION 4

the blunt forms were changed into two different shapes to compare the differences in the wind pressure acting on them; while there is no visible difference in pressure between the two forms from the Flow Design output, the curved face on the right would experience less pressure build-up than the straight face on the left

Flow Design shows no visible difference between the wind pressures on the leeward sides of the two forms



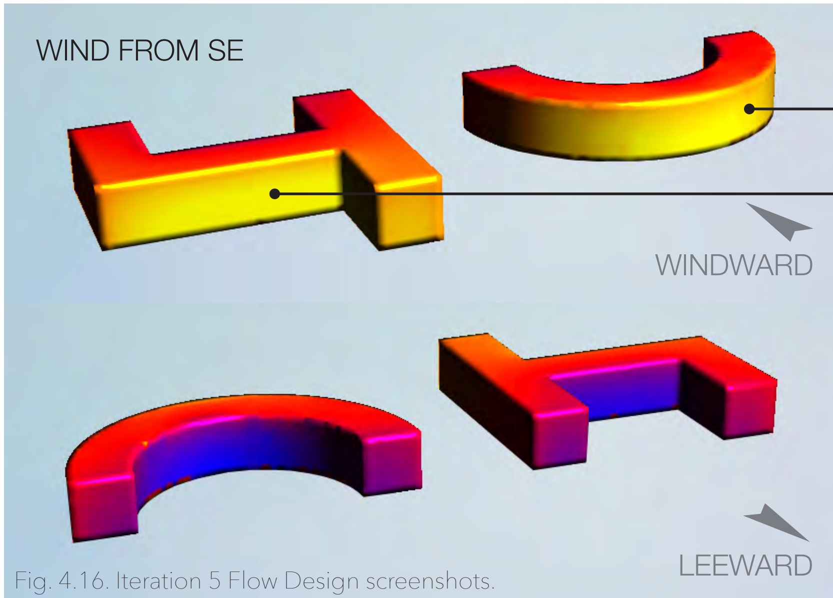


Fig. 4.16. Iteration 5 Flow Design screenshots.

ITERATION 5

curved form was kept in this iteration for its good aerodynamic properties

in next iteration, curve this form to reduce the wind pressure build-up on it

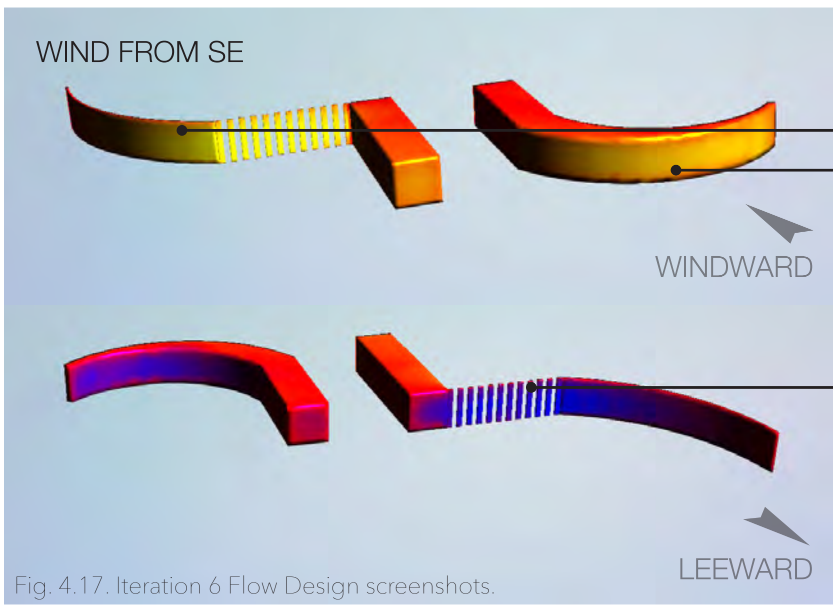


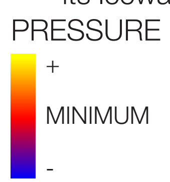
Fig. 4.17. Iteration 6 Flow Design screenshots.

ITERATION 6

form was curved to reduce the wind pressure acting on it

form is kept curved in this iteration for its good aerodynamic properties

part of the wall was made porous to reduce the wind force on its leeward side



ITERATION 7

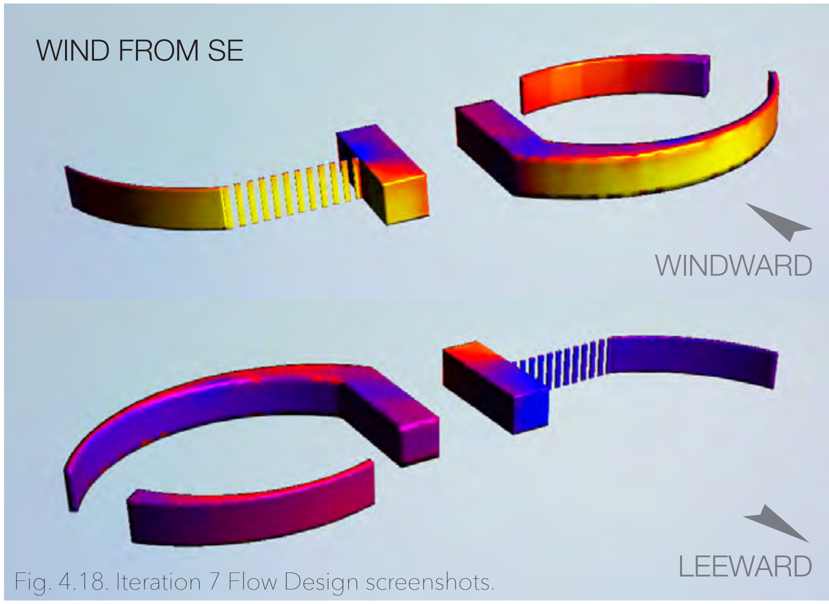


Fig. 4.18. Iteration 7 Flow Design screenshots.

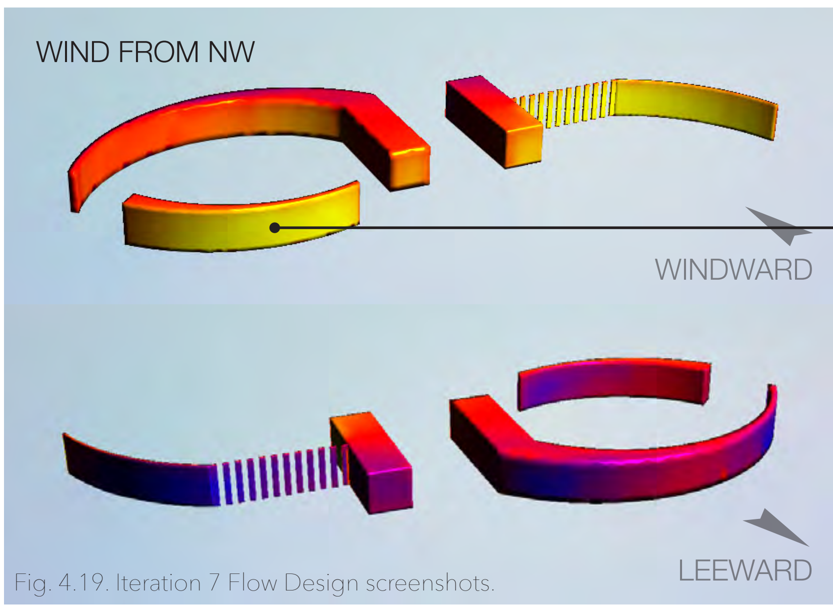
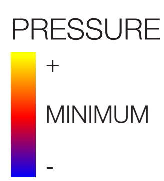


Fig. 4.19. Iteration 7 Flow Design screenshots.

added wall to create sheltered space is curved into the direction of the wind to reduce pressure on it when wind blows from the NW



ITERATION 8

rotating and staggering the forms shelters this part of the building that is leeward of the smaller form, reducing wind pressure on that area

the form of the smaller building is curved into the direction of the wind to reduce pressure on it when wind comes from the SE

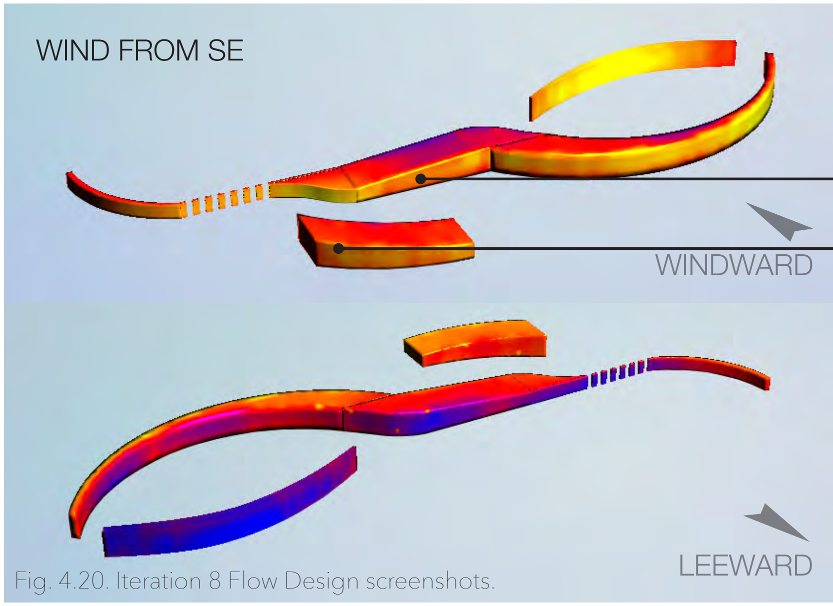


Fig. 4.20. Iteration 8 Flow Design screenshots.

all edges of forms are curved to reduce wind pressure build-up on them

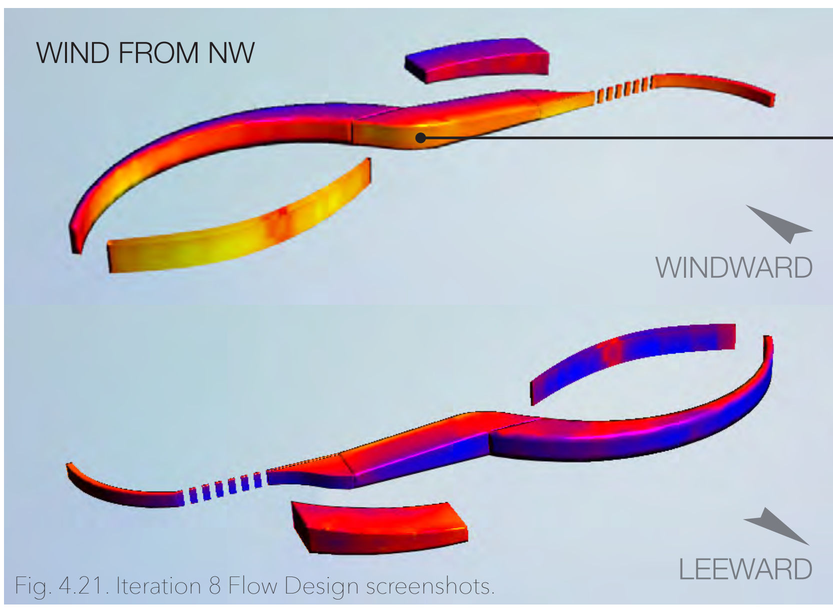
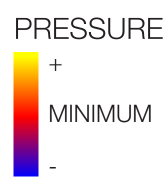


Fig. 4.21. Iteration 8 Flow Design screenshots.



ITERATION 9

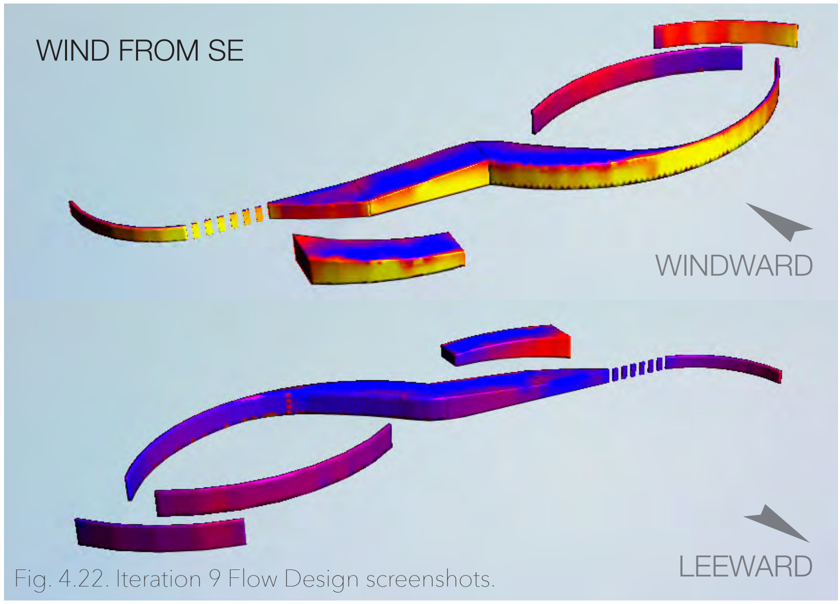


Fig. 4.22. Iteration 9 Flow Design screenshots.

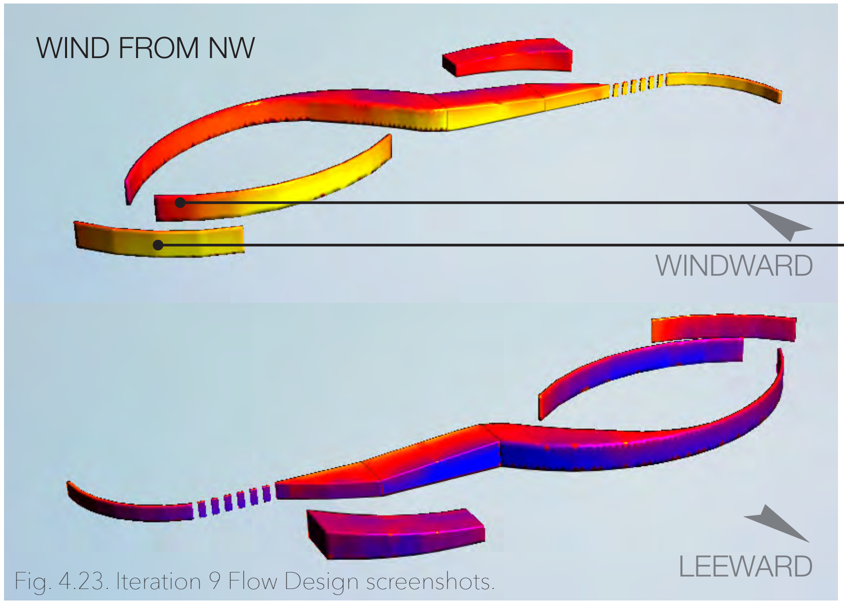


Fig. 4.23. Iteration 9 Flow Design screenshots.

the added wall to create a high-speed wind stream shelters this area of the wall when wind comes from the NW, reducing wind pressure acting on it

added wall is made curved into the direction of the wind to reduce pressure on it when wind blows from the NW

ITERATION 10

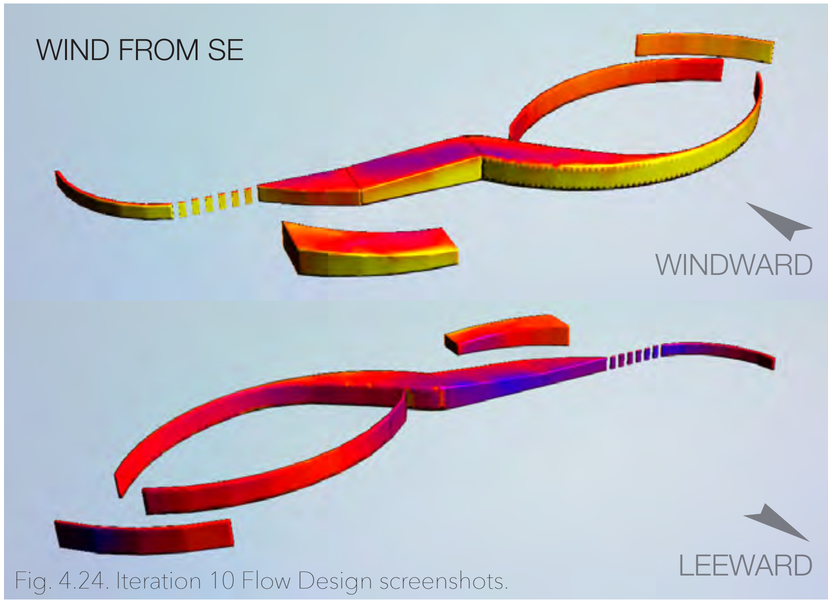


Fig. 4.24. Iteration 10 Flow Design screenshots.

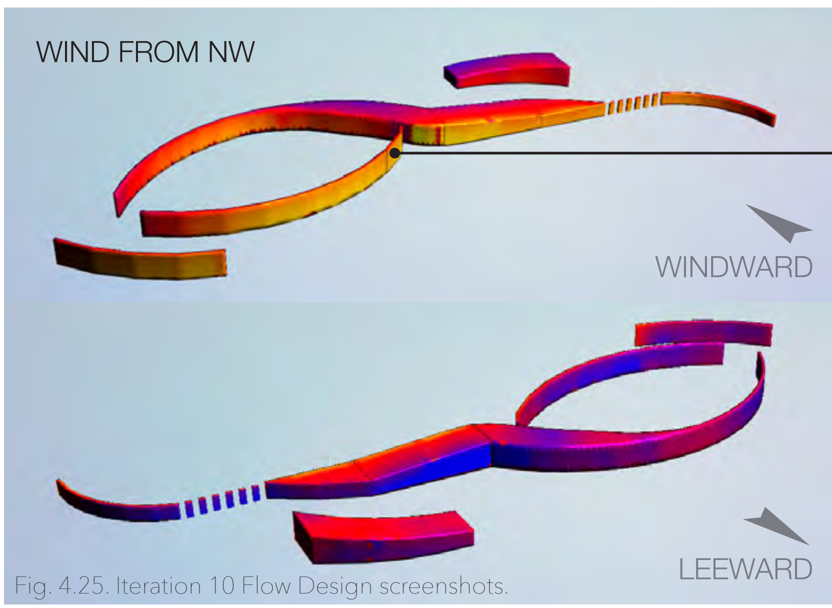
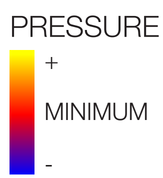


Fig. 4.25. Iteration 10 Flow Design screenshots.

the extension of the wall, which is the only alteration in this iteration, has little impact on wind pressure



ITERATION 11

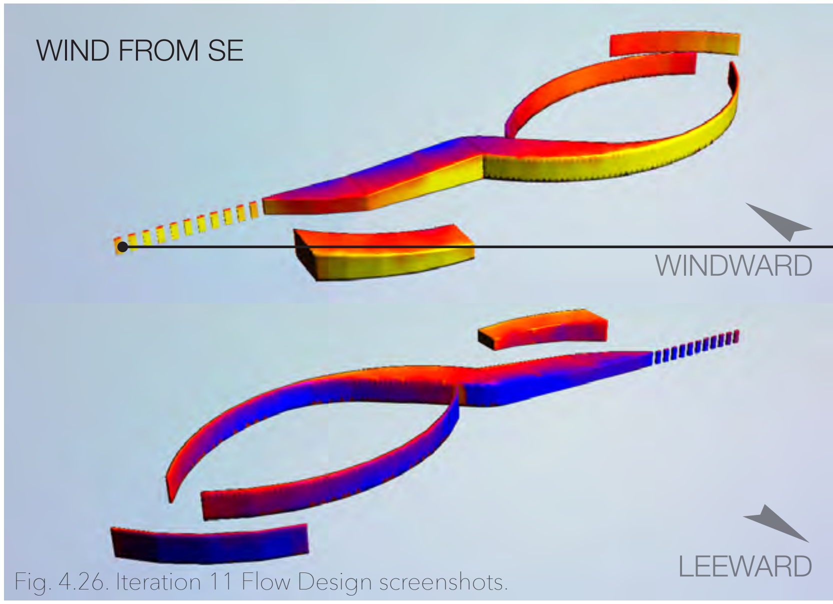


Fig. 4.26. Iteration 11 Flow Design screenshots.

the removal of the curved wall, which is the only alteration in this iteration, has little impact on wind pressure

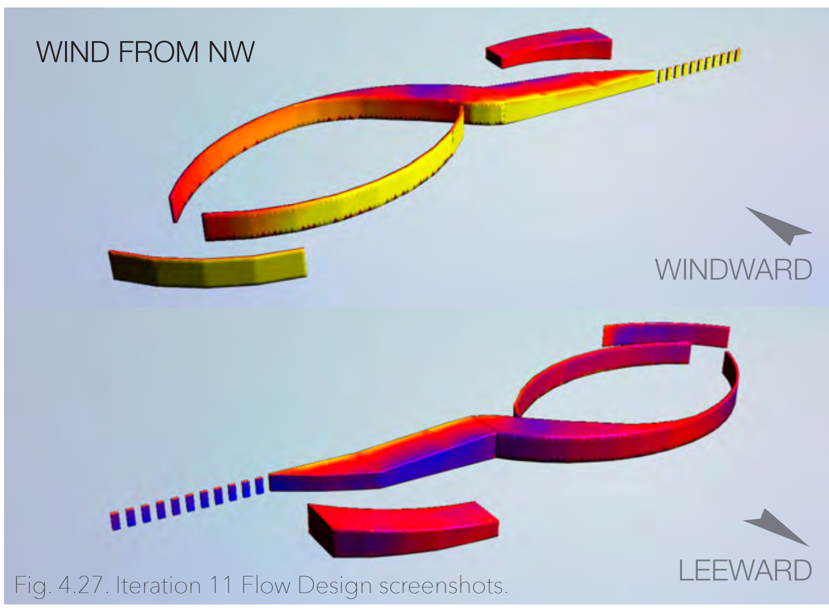


Fig. 4.27. Iteration 11 Flow Design screenshots.

PRESSURE
+
MINIMUM
-

WIND AFFECTS STRUCTURE

HOW WIND AFFECTS STRUCTURE

When wind pressure acts on a building, it exerts load on the building which must be resisted by the building's structural system.[1] Because these wind loads usually act laterally, their resistance often requires different structural systems than those used to resist vertical gravity loads.[2] The ways in which wind loads act on a building therefore should be considered in the selection and design of the building's structural system.

There are several types of wind loads, and each type induces a different building response. **Alongwind load** is the wind load that acts in the direction parallel to that of the mean wind velocity, and causes the building to move in that same direction (Fig. 5.1).[3] Similarly, **crosswind load** acts on the building perpendicular to the direction of the mean wind velocity, and the crosswind response of the building is movement in the same direction (Fig. 5.2).[4] Crosswind response of slender buildings may be induced by vortex shedding.[5] As wind blows around a building, vortices form on the sides of the building and then detach from the building.[6] They tend to do this in a pattern, shedding alternately from each side (see Fig. 3.60 on page 81).[7] As they shed, they generate suction,[8] which causes forces to act alternately on the sides of the building in the crosswind direction.[9] This makes the building oscillate in the crosswind direction.[10] Finally, **torsional load** causes the building to twist about its vertical axis (Fig. 5.3).[11]

While alongwind, crosswind and torsional loads act laterally, **uplift** (Fig. 5.4) is wind force that acts upwards, mainly on large roofs.[12] As wind flow detaches from the building surface at its windward edges, an area of negative pressure is created over the roof[13] that physically sucks the roof upwards.[14] Building structures should be designed to resist both lateral and uplift forces, although the type of force that tends to govern the design of the structural system depends on the building's shape and **aspect ratio**.[15] In general, the resistance of lateral loads and overturning governs the design of slender buildings, while uplift

Alongwind load
Wind load acting in the direction parallel to the mean wind velocity.

Crosswind load
Wind load acting in the direction perpendicular to the mean wind velocity.

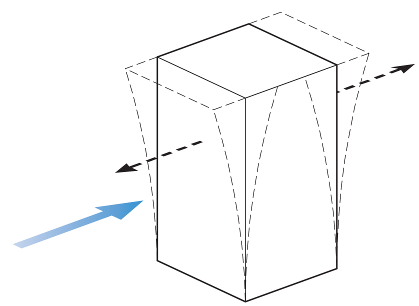


Fig. 5.1. Alongwind load response.

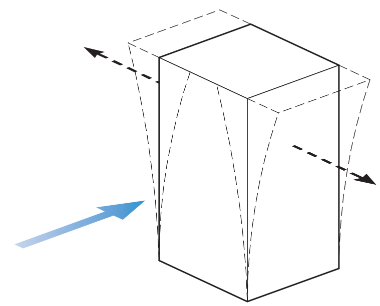


Fig. 5.2. Crosswind load response.

Torsional load
Wind load that induces twisting about the vertical axis.

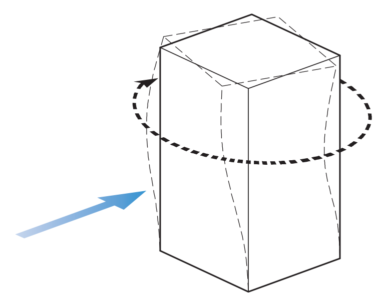


Fig. 5.3. Torsional load response.

Uplift
Wind force acting upwards in the direction perpendicular to the mean wind velocity.

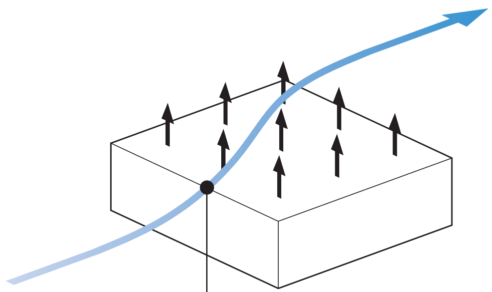


Fig. 5.4. Upift.

Aspect ratio
Ratio of height to width.

Static wind load
Wind load that maintains a consistent magnitude and location over a period of time.

Dynamic wind load
Wind load that rapidly changes in magnitude or location.

Fundamental period
The length of time required to complete one oscillation.

Quasi-static wind load
Static wind load with an increased magnitude to account for the wind load's dynamic nature.

forces are of more concern in the design of broad, low buildings.[16] To resist uplift forces, all structural members should be connected to create a continuous load path that anchors the roof to the foundation, to transfer the uplift forces down to the foundation through the structural members.[17] This may be achieved with reinforcing bars in concrete or masonry walls, anchoring steel columns at their bases with anchor bolts, or using strong metal connectors between members of wood frame systems.[18] While uplift is an important consideration in the design of structural systems to resist wind loads, it is not considered in the design method of this thesis because the CFD software that is used does not simulate wind uplift effects. This design method therefore only considers the resistance of lateral wind loads. However, a consideration of uplift could be integrated into the method if the software were to be improved in the future to be able to simulate uplift forces.

Alongwind, crosswind and torsional loads all have both static and dynamic components.[19] **Static wind load** is caused by the mean wind pressure acting on a building over a period of time, and maintains a consistent magnitude and location.[20] As described in the previous chapter, the wind pressure, and therefore the static wind load, acting on a building can be affected by the building's form.[21] **Dynamic wind loads** rapidly change in magnitude or location over much shorter periods of time.[22] They are caused by unsteady wind pressures, which are the result of wind turbulence or the separation of the wind flow off the building surface at the windward edges of the building.[23] Whether a certain load acts statically or dynamically depends on the stiffness of the structure on which it is exerted.[24] A load that is applied to the structure for a longer length of time than the structure's **fundamental period**[25] acts as a static load, whereas if it is applied for a shorter length of time, it acts as a dynamic load.[26] Stiff structures have a shorter fundamental period than more flexible structures, so a certain load, applied for a certain length of time, could be static for a stiffer structure and dynamic for a more flexible structure, putting more strain on the flexible structure.[27] For the purposes of simplifying wind loads, a **quasi-static wind load** assumes that the wind acts as a static load, but the magnitude of that load is increased to account for the dynamic nature of the wind.[28] All of these wind loads, and their static and dynamic components, need to be accounted for when designing a building's structural system.

There are several factors that affect how much a building responds to wind loads:[29]

WIND VELOCITY
Higher-speed winds generally exert more wind pressure on buildings and induce more building response.[30]

GEOMETRY
Streamlined shapes generally experience lower wind loads because the wind cannot build up enough pressure on a single, blunt side.[31] This causes streamlined buildings to experience less wind-induced response.

EXPOSURE
The more exposed a building is to the oncoming wind, the more wind load will be exerted on the building, causing the building to move more in the wind.[32] Generally, surface features surrounding the building shelter it from the wind and reduce the wind load that acts on it.[33] However, surrounding features can sometimes accelerate the wind flow around the building, causing the building's response to the wind to be greater.[34]

ORIENTATION
If a building is oriented so that its most sensitive direction to the wind is facing away from the oncoming wind flow, the building will experience less wind-induced response.[35]

MASS AND STIFFNESS
Heavier, stiffer structures respond less to the wind than lighter or more flexible structures because of their shorter fundamental periods.[36]

STRUCTURAL DAMPING LEVEL
Structural damping decreases the amount by which the building moves in the wind. Some damping is provided by the stiffness of the building's structural system, but supplementary dampers such as tuned mass dampers, tuned liquid dampers, viscous dampers, and active damping systems, can increase the level of damping that is provided to the building.[37] The higher the level of structural damping, the less the building responds to the wind.[38]

In addition to affecting the design of a building's structural system, wind also affects cladding design as it exerts pressure across the surface of the cladding.[39] The amount of wind pressure that acts on small areas of the cladding can vary greatly across the building's surface, as the magnitude of the wind pressure at any given location is dependent on the building's shape and orientation.[40] For this reason, some small elements of the cladding such as mullions, glazing panels, sheathing, and shingles must be designed to withstand increased wind pressures over their small surface areas.[41] These increased design wind pressures are often mandated by building codes.[42] The various pressures that are exerted across the building's surface are averaged to obtain the overall wind load values that are used to design the building's structural system.[43]

For the third step in the design method, the wind pressure information that is provided by the CFD software is input into the FEA software to predict how the building will react to combined wind and gravity loading. This allows the architect to design the building's structural system, by developing models of single structural bays. Based on the deflection animation and the colour gradient that represents the displacement of each point of the model that is provided by the FEA software, the architect can see where and how much the bay will deflect in the wind and under gravity. The architect can then stiffen the bay against this deflection, and run the finite element analysis on multiple iterations of bays, with the goal of increasing the stiffness of the assembly each time. This process is repeated until the building's structural system can adequately resist large movements in the wind.

STRUCTURAL SYSTEMS LIBRARY

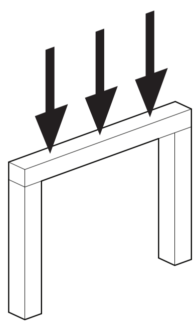


Fig. 5.5. Gravity loads.

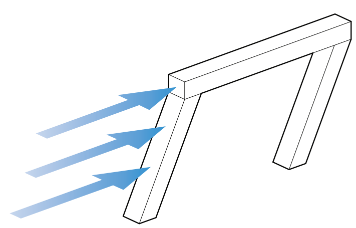


Fig. 5.6. Wind loads.

A structural framing system can resist gravity loads (Fig. 5.5), but must be braced, or stiffened, to resist movement under lateral wind loads (Fig. 5.6).[44] This can be done with diaphragms that make the entire wall or floor plane act as a unified whole to resist lateral loads (Fig. 5.7),[45] bracing that stabilizes the frame under lateral loads (Fig. 5.8),[46] or moment-resisting connections that don't allow the structural members to rotate under lateral loads (Fig. 5.9).[47] Earthquake loads are also a type of lateral load,[48] and may be resisted with these same structural systems that are used to resist wind loads.[49]

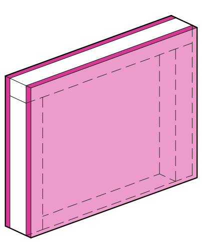


Fig. 5.7. Diaphragm.

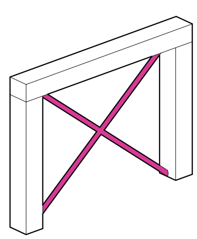


Fig. 5.8. Bracing.

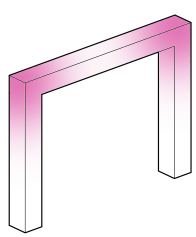


Fig. 5.9. Moment-resisting connections.

Fig. 5.10. Plywood on wood framing.

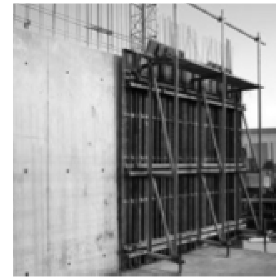


Fig. 5.11. Solid concrete wall.

Fig. 5.12. Masonry wall.

DIAPHRAGMS

Diaphragms are rigid walls that are continuous through the height of the building.[50] They resist the tendency of the building floors to slide relative to one another when subjected to lateral wind loads[51] by acting in bending as stiff vertical cantilevers.[52] They are made of surfacing that is attached to the structural framing to make the structural members act as a unified whole in resisting lateral wind loads,[53] and can take the form of plywood attached to wood framing (Fig. 5.10), solid concrete walls (Fig. 5.11), or masonry walls (Fig. 5.12).[54] Without surfacing, individual structural members in a frame would move to the side under lateral loads (Fig. 5.13).[55] The surfacing makes the entire wall act as a cohesive unit that resists rotation under wind loads.[56] This tendency to want to rotate induces tension in the windward side of the wall and compression in the leeward side, so the connections at the base of the diaphragm must resist these forces and carry them down into the foundation (Fig. 5.14).[57] There should be minimal openings in these walls to ensure that they are effective at resisting wind loads.[58] They may either be placed symmetrically within the building's exterior walls, or be used as interior walls, typically wrapping around the building's central core.[59] Regardless of their placement, a minimum of two perpendicular diaphragms are required within the building to provide resistance against the wind that could come from any direction.[60]

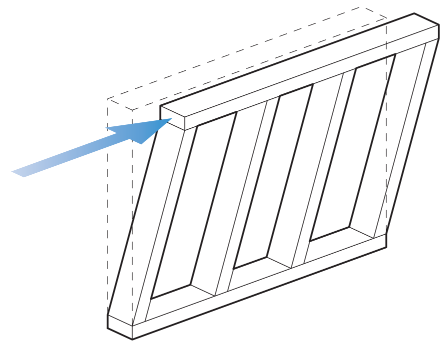


Fig. 5.13. A frame without surfacing moves to the side under lateral loads.

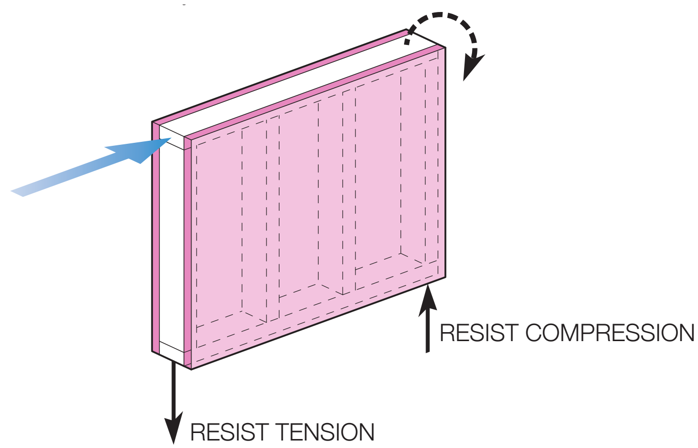


Fig. 5.14. A diaphragm subjected to lateral loads.


Fig. 5.15. Steel framing.


Fig. 5.16. Wood framing.

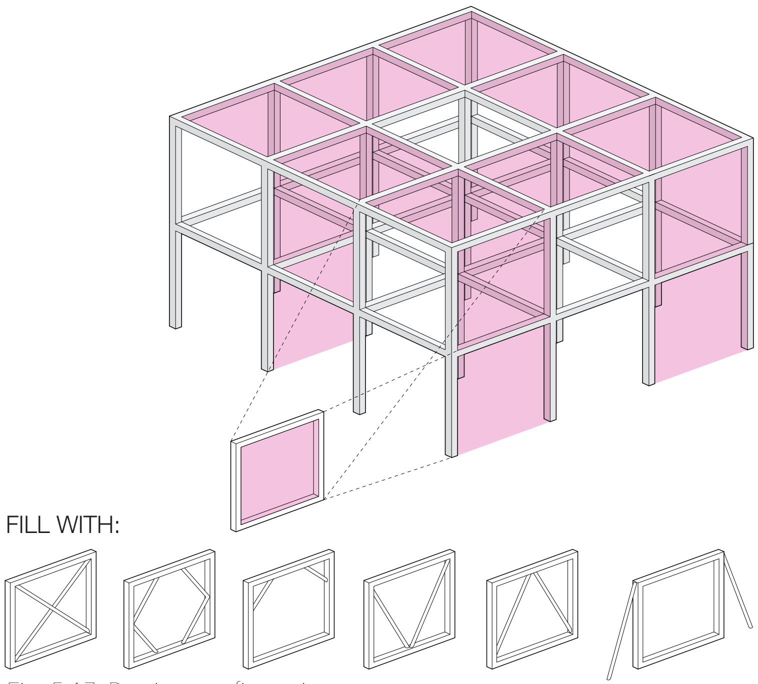


Fig. 5.17. Bracing configurations.

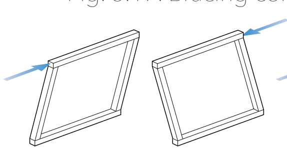


Fig. 5.18. Wind load on a frame.

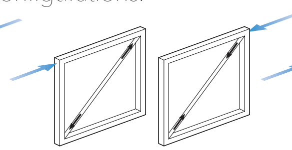


Fig. 5.19. One diagonal member.

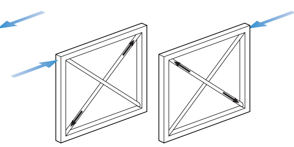


Fig. 5.20. Two diagonal members.

BRACING

Bracing may also be used to stabilize a structural frame against lateral wind loads. The diagonal members work to resist shear[61] as they increase they rigidity of the frame and reduce the bending stresses in the beams and columns.[62] They may be made out of steel (Fig. 5.15) or wood (Fig. 5.16) framing.[63] There are many configurations of diagonal bracing members that may be inserted within a frame (Fig. 5.17).[64] If only one diagonal member is used, it must be able to resist both tension and compression as the wind load could act on either side of the frame (Fig. 5.18) to elongate or shorten the diagonal member (Fig. 5.19).[65] If there are at least two diagonal members, however, it is not necessary for both of them to be good in both tension and compression, as one can work in tension to stiffen the frame when the wind comes from one direction, and the other can work in tension to stiffen the frame against wind from the other direction (Fig. 5.20).[66] While bracing is efficient at stiffening frames against wind loads, the insertion of the diagonal members into the building's framing is not always conducive to the interior building layout.[67]

Fig. 5.21. Steel plates and fasteners.

Fig. 5.22. Bolted connection.

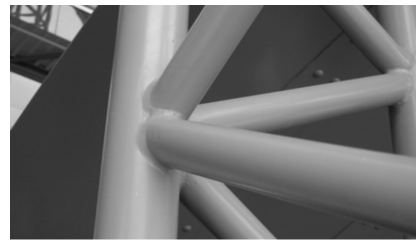


Fig. 5.23. Welded connection.

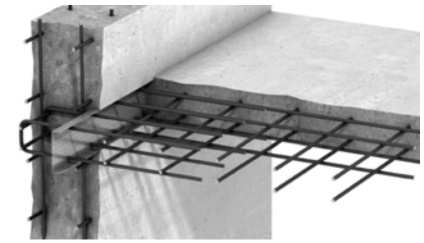


Fig. 5.24. Steel-reinforced concrete joint.

MOMENT-RESISTING CONNECTIONS

Moment-resisting connections, which occur at the joints between the beams and columns in a frame and not within the frame's opening, prevent the frame's structural members from rotating relative to one another under lateral loads.[68] They may be created with steel plates and fasteners connecting wooden members (Fig. 5.21),[69] bolted (Fig. 5.22) or welded (Fig. 5.23) connections between steel members, or steel-reinforced joints between concrete members (Fig. 5.24).[70] These connections stiffen the entire frame so that it deforms as a cohesive unit to absorb wind and gravity loads (Fig. 5.25).[71] While they are less efficient at resisting shear than diagonal bracing members, the lack of obstructions within the frame makes it easier to plan interior building layouts and exterior window and door placements.[72]

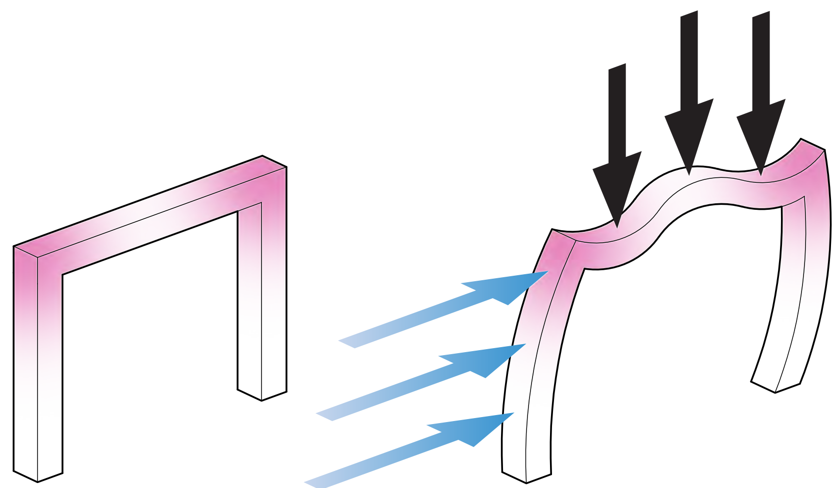


Fig. 5.25. The frame deforms as a cohesive unit to absorb wind and gravity loads.

STRUCTURAL SYSTEM SELECTION

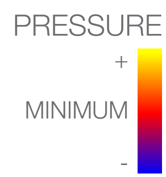
In the two previous steps of the design method, the wind effects library and the aerodynamic forms library could be referred to for design strategies to manipulate the wind conditions around the building and reduce the wind pressure acting on the building. Similarly, the structural systems library in this chapter described several systems that can be used to resist wind loads. However, the structural systems library is not intended to be a reference during the design process, as for the purposes of the development of the design methodology, a steel-frame system has been chosen and this step has been developed specifically for the planning of this type of structural system. The modular nature of a steel-frame system allows the architect to design small units of structure that are repeated throughout the building. This creation of a single unit may be applied to buildings of various sizes, as the units may be repeated as many times as necessary. Its modularity also allows the architect to avoid modeling and testing the entire building's structure, instead just designing a few different structural units. The simplicity of this system provides an appropriate base with which to develop a methodology that could then potentially be applied to the design of one of the other structural systems described in the structural systems library.

FEA ITERATIONS TO DEVELOP STRUCTURAL SYSTEM

1. PRESSURE ZONES

The first step in the structural system development is to divide the building form into different pressure zones, based on the colour gradients representing the wind pressure on the model's surface that were obtained from Flow Design in the previous chapter (Fig. 5.26). The building is divided into seven pressure zones (Fig. 5.27) based on the areas that are subject to the same amount of wind pressure according to the colour gradients. The reasons for these variations in wind pressure across the model's surface, such as form, exposure, orientation, and porosity, are described in the previous chapter.

Once the form has been divided into these pressure zones, the average positive and negative wind pressure values for each zone are obtained from the wind pressure colour gradients for each of the site's two predominant wind directions. These values are shown in the pressure zone matrix (Fig. 5.28). However, the accuracy of these values depends on the level of accuracy that may currently be obtained from the CFD software, and as such, they may not necessarily reflect the wind pressure that would be exerted on the building in reality. For the purposes of this method, each zone is assumed to be subjected to the highest combined positive and negative wind pressure, out of the values obtained from both wind directions. This ensures that the building's structure will be able to withstand the wind pressure within all of the site's predominant wind directions.



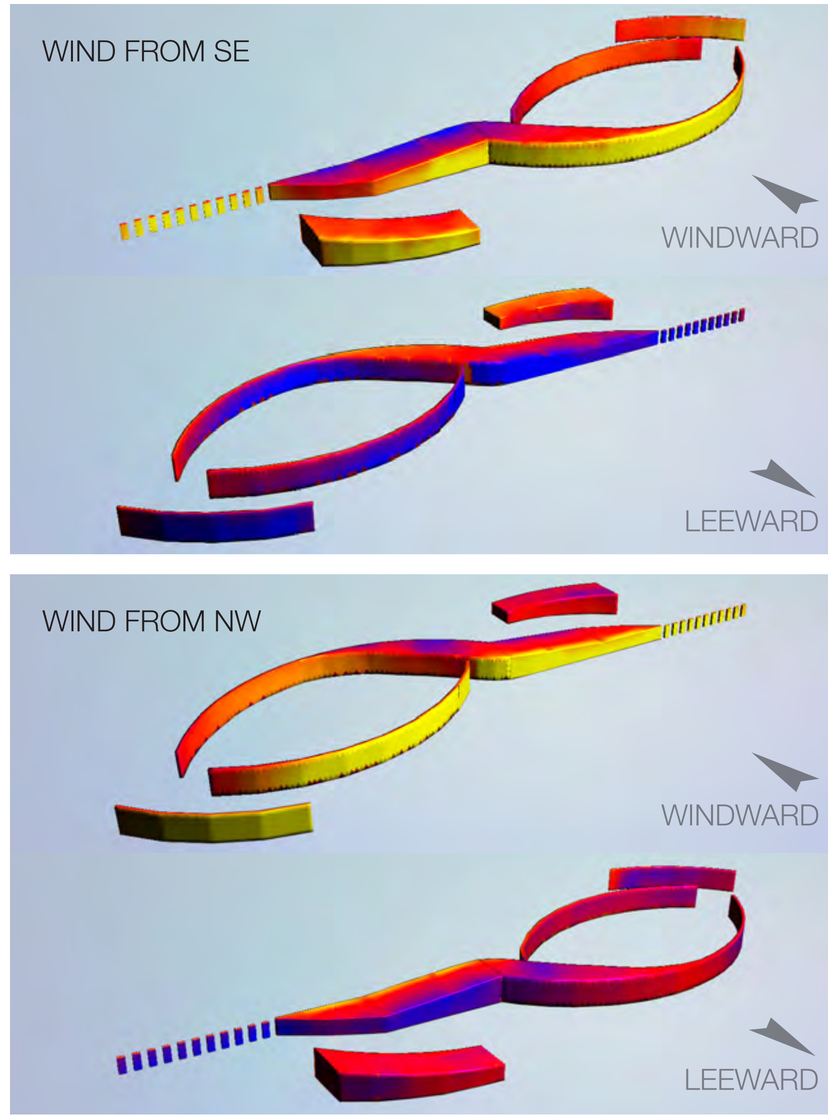


Fig. 5.26. Wind pressure gradients from Flow Design.

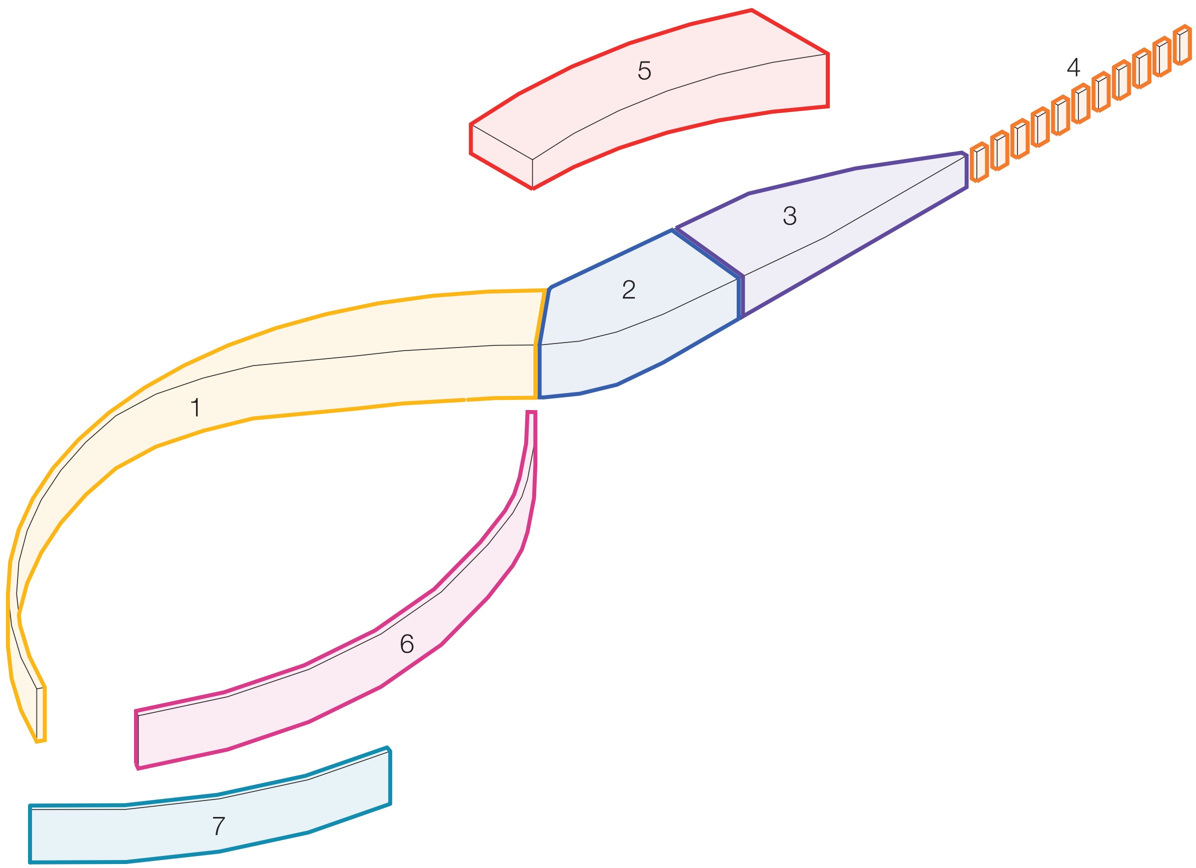


Fig. 5.27. The building divided into pressure zones.

WIND DIRECTION	PRESSURE	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5	ZONE 6	ZONE 7
SE	WINDWARD LEEWARD	32 Pa -28 Pa	32 Pa -35 Pa	5 Pa - 35 Pa	32 Pa - 20 Pa	32 Pa - 10 Pa	5 Pa -20 Pa	8 Pa -20 Pa
NW	WINDWARD LEEWARD	1 Pa -15 Pa	15 Pa -23 Pa	15 Pa - 36 Pa	15 Pa - 36 Pa	1 Pa - 12 Pa	10 Pa -10 Pa	10 Pa -22 Pa

Fig. 5.28. Pressure zone matrix.

2. FEA OF BUILDING MASSING

The wind pressure values for the highest combined positive and negative pressure that were obtained from Flow Design in the previous step, as well as gravity loading, are then input into Scan&Solve and applied to the massing model of each pressure zone, as shown for zone 1 (Fig. 5.29). The colour gradient that represents the displacement of each point of the model, as well as the deflection animation (Fig. 5.30), reveal areas within the zone that may deflect more while under wind load than other areas within the zone. In the case of zone 1, the form deflects the most at the right side, where the massing is the thinnest. As such, zone 1 has been divided into two sub-zones: 1A and 1B (Fig. 5.31). These sub-zones are subjected to the same amount of wind pressure, but require different structural configurations due to the difference in geometry thickness. This process is repeated with each of the other zones to determine if more sub-zone divisions are required.

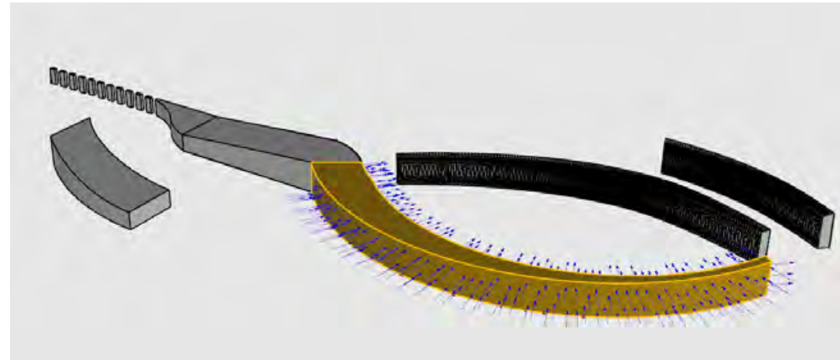


Fig. 5.29. Loading applied to zone 1 in Scan&Solve.

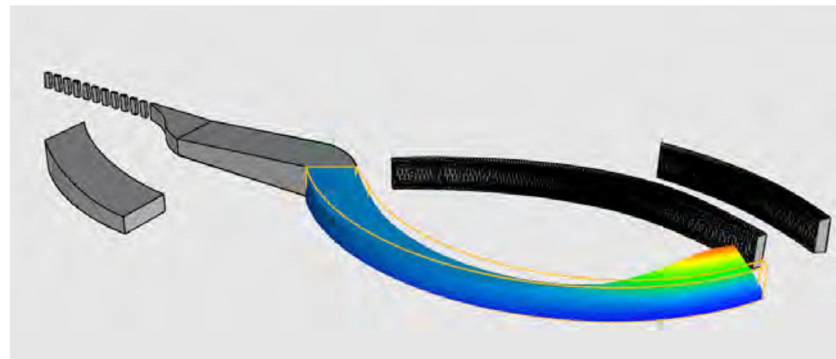


Fig. 5.30. Deflection animation of zone 1 from Scan&Solve.

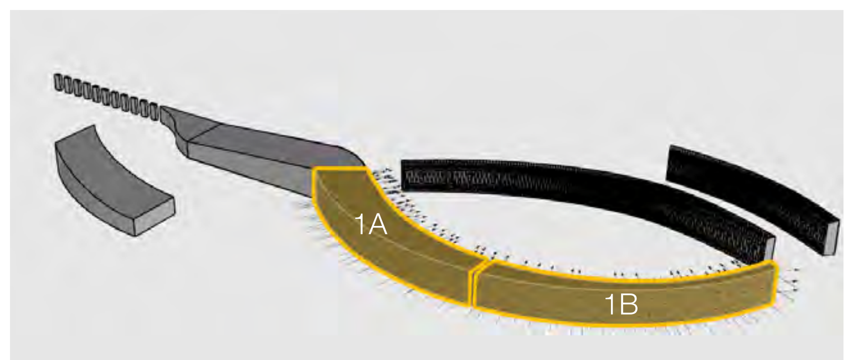


Fig. 5.31. Zone 1 divided into sub-zones.

3. STRUCTURAL BAYS

A structural bay is then modeled for zone 1A, and tested with Scan&Solve by inputting gravity loading and the wind pressure for zone 1. The deflection of the bay in the wind is observed with the displacement colour gradient and deflection animation. The colour gradient that represents displacement allows the architect to easily read where and by how much the model will move under load, although the accuracy of this quantitative data depends on the accuracy of the FEA software. The deflection animation allows the architect to actually see how the structural bay would deflect to know how and where to stiffen the model in the next iteration. It should be noted that the deflection animations are exaggerated to more obviously show where the deflection would occur. If there is too much deflection under the input loading, the architect adjusts the model of the bay to increase its stiffness. This may be accomplished by reducing column spacing, increasing member sizes, or adding bracing. This process is repeated until a bay is developed that has appropriate column spacing, member sizes, and bracing to resist large movements in the wind.

The first four iterations, for which the displacement colour gradients and deflection animations are shown, were used to develop a structural bay for zone 1A, and the following four iterations develop a bay for zone 1B. The process is then repeated for zones 2 through 7 to develop a structural bay for each pressure zone within the zone's specified wind pressure conditions. Reducing the scope of the structural design to a single structural bay allows the architect to avoid the time-consuming task of modeling and testing the entire building's structure, while still being able to understand the column spacing, member sizes, and bracing that will be required throughout the building.

This step in the design method does not intend for the architect to replace the structural engineer. In a later design phase, the structural engineer would perform a more thorough structural design and analysis and would likely make adjustments to the structural bay that is developed with this step. The importance of the method is that it provides the architect with a sense of the approximate structural spacing, as well as an understanding that some form of bracing will be required. The architect can account for this while designing the building interior, so that no design decisions compromise the approximate structure that must be accommodated. This method provides a way of integrating structural considerations into the initial building design, which improves collaboration between the architect and the structural engineer throughout many design phases.

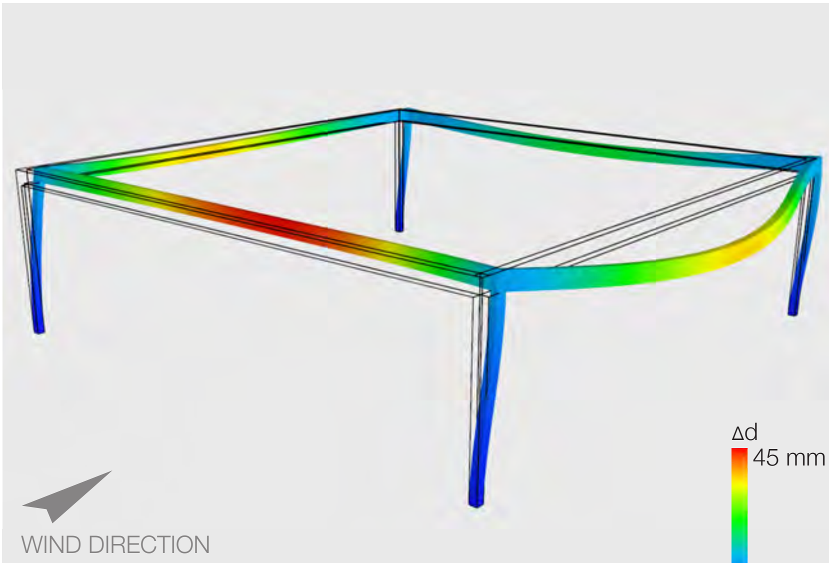


Fig. 5.32. Zone 1A iteration 1 Scan&Solve screenshot.

ZONE 1A | ITERATION 1

BAY DIMENSIONS	15m x 15m, to fit one bay within 15m wide building
BEAM SECTIONS	200mm x 400mm
COLUMN SECTIONS	200mm x 200mm
OBSERVATIONS	The bay will deflect 45mm in some places, which is excessive.
CHANGES TO MAKE	In the next iteration, reduce the column spacing to stiffen the bay and reduce its deflection.

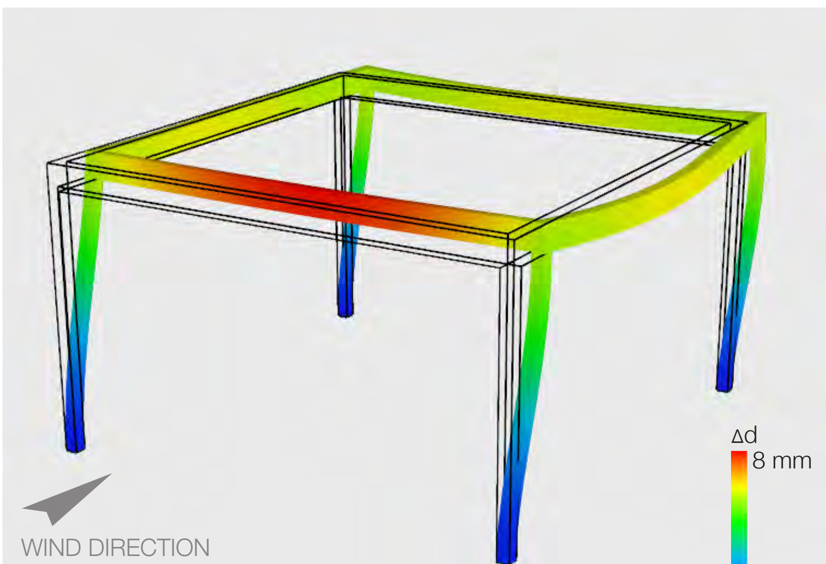


Fig. 5.33. Zone 1A iteration 2 Scan&Solve screenshot.

ZONE 1A | ITERATION 2

BAY DIMENSIONS	7.5m x 7.5m, to fit two bays within 15m wide building
BEAM SECTIONS	200mm x 400mm
COLUMN SECTIONS	200mm x 200mm
COMMENTS	The bay will only deflect 8mm at most, so maintain this column spacing so the bays can fit evenly within the building width.
CHANGES TO MAKE	In the next iteration, add bracing to further stiffen the structure.

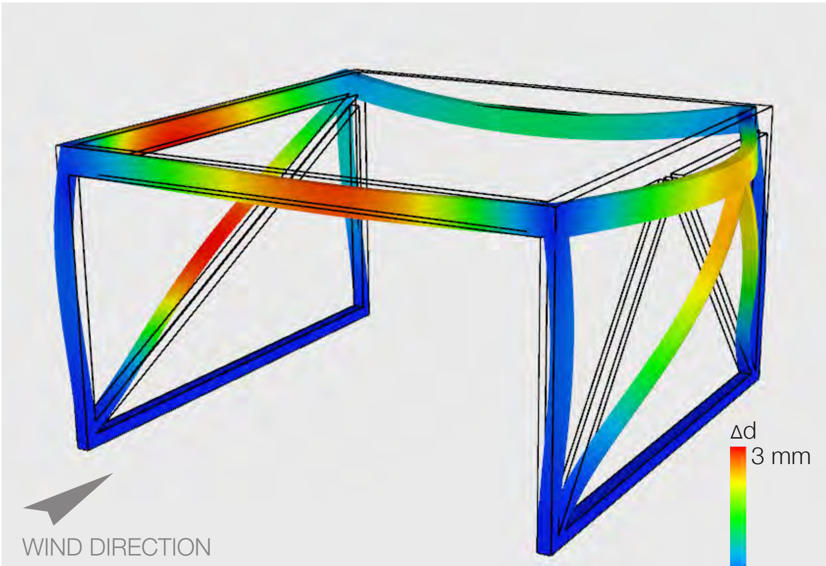


Fig. 5.34. Zone 1A iteration 3 Scan&Solve screenshot.

ZONE 1A | ITERATION 3

BAY DIMENSIONS	7.5m x 7.5m
BEAM SECTIONS	200mm x 400mm
COLUMN SECTIONS	200mm x 200mm
COMMENTS	Different types of bracing have been added on each side of the bay to compare their deflections. Two members deflect less than one member, so use two members in each frame.
CHANGES TO MAKE	In the next iteration, try cross-bracing to compare the deflection, although the deflection of this upside-down V-bracing is adequately low so that it could be used in frames where openings are needed.

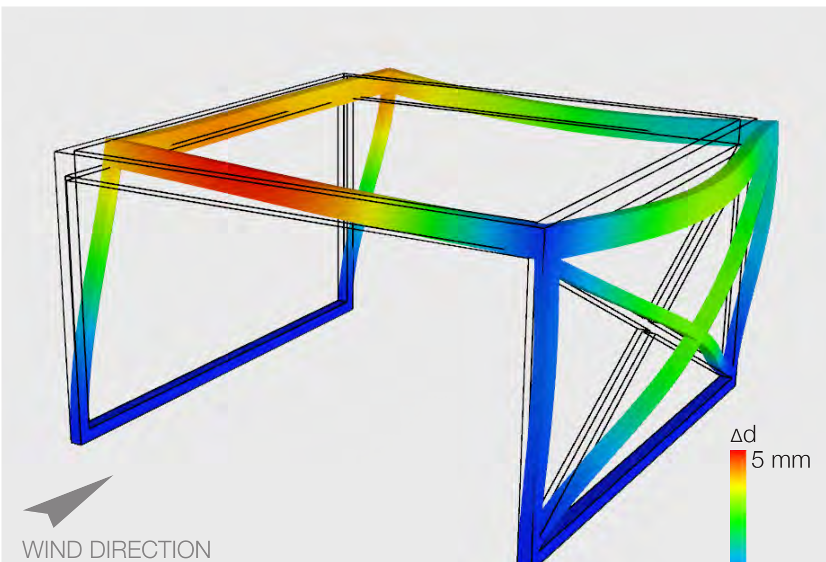


Fig. 5.35. Zone 1A iteration 4 Scan&Solve screenshot.

ZONE 1A | ITERATION 4

BAY DIMENSIONS	7.5m x 7.5m
BEAM SECTIONS	200mm x 400mm
COLUMN SECTIONS	200mm x 200mm
COMMENTS	Cross-bracing has been tested on one side of the bay, and deflects less than the upside-down V-bracing of the previous iteration.
CONCLUSIONS	Therefore, use this column spacing and these member sizes, and insert cross-bracing or V-bracing within the frames that are parallel to the wind direction in zone 1A.

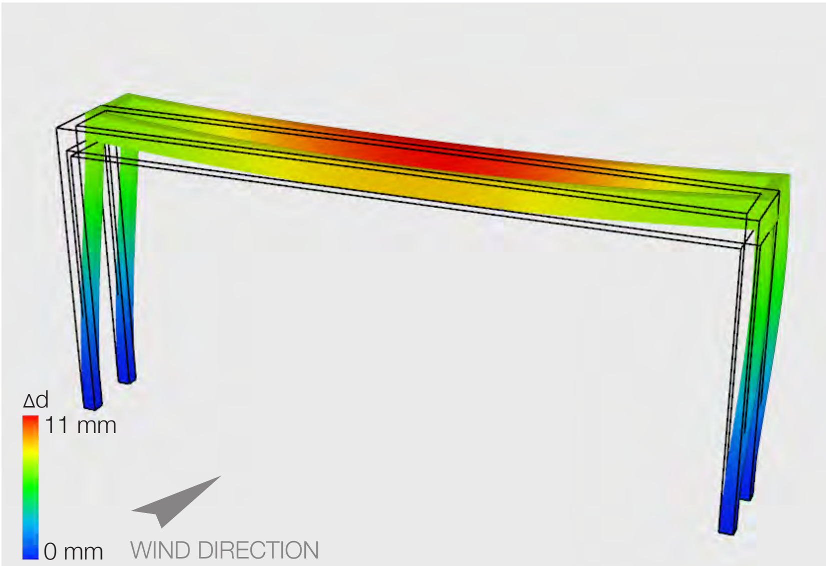


Fig. 5.36. Zone 1B iteration 1 Scan&Solve screenshot.

ZONE 1B | ITERATION 1

BAY DIMENSIONS	10m x 1m, because zone 1B is a wall and not occupiable building space
BEAM SECTIONS	200mm x 400mm
COLUMN SECTIONS	200mm x 200mm
COMMENTS	No bracing is used in this iteration. The bay will deflect 11mm.
CHANGES TO MAKE	In the next iteration, decrease the lengthwise column spacing, increase the wall thickness, and add bracing to increase the bay's stiffness.

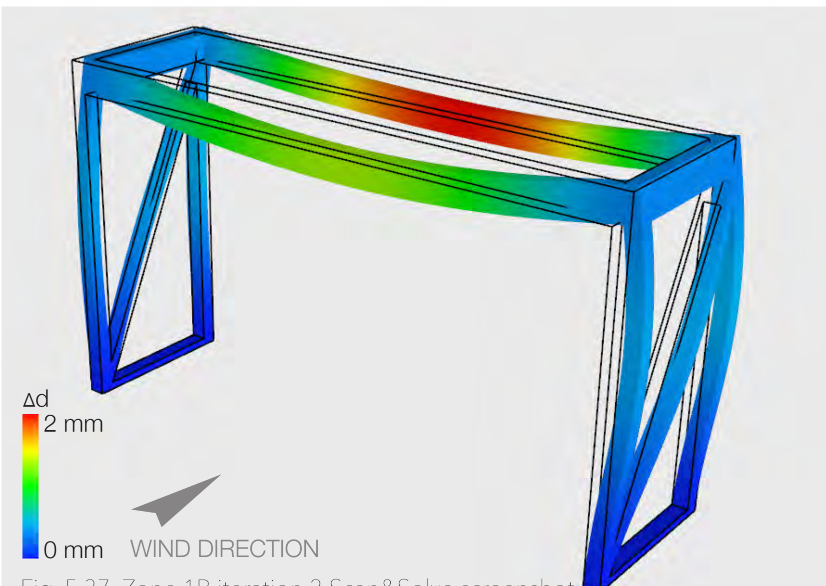


Fig. 5.37. Zone 1B iteration 2 Scan&Solve screenshot.

ZONE 1B | ITERATION 2

BAY DIMENSIONS	7.5m x 2m, to try a shorter and wider bay
BEAM SECTIONS	200mm x 400mm
COLUMN SECTIONS	200mm x 200mm
COMMENTS	A single bracing member is inserted in the frames that are parallel to the wind direction. The deflection is low, at 2mm.
CHANGES TO MAKE	In the next iteration, see if a shallower wall will still experience an adequately small amount of deflection under load.

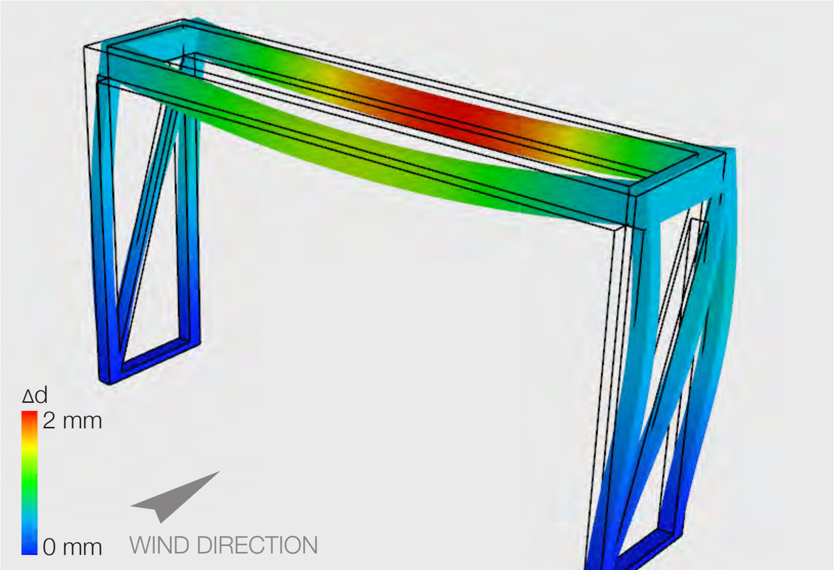


Fig. 5.38. Zone 1B iteration 3 Scan&Solve screenshot.

ZONE 1B | ITERATION 3

BAY DIMENSIONS	7.5m x 1.5m, to try a shallower bay
BEAM SECTIONS	200mm x 400mm
COLUMN SECTIONS	200mm x 200mm
COMMENTS	The deflection is adequately low at 2mm.
CHANGES TO MAKE	In the next iteration, see if a shallower wall will have still have an adequately small amount of deflection under load.

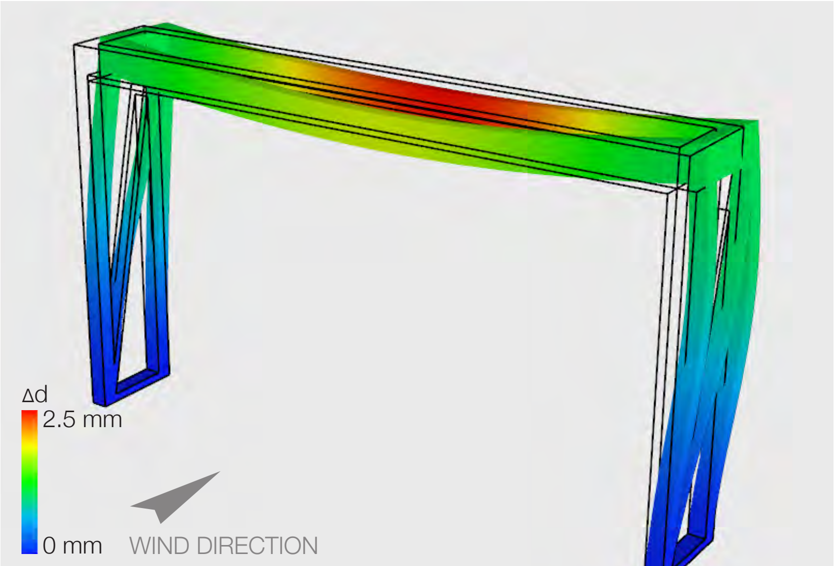


Fig. 5.39. Zone 1B iteration 4 Scan&Solve screenshot.

ZONE 1B | ITERATION 4

BAY DIMENSIONS	7.5m x 1m
BEAM SECTIONS	200mm x 400mm
COLUMN SECTIONS	200mm x 200mm
COMMENTS	The deflection is adequately low at 2.5mm, and the wall is thinner than the previous iterations.
CONCLUSIONS	Therefore use this column spacing and these member sizes, and insert bracing within the frames that are parallel to the wind direction in zone 1B.

4. STRUCTURAL SYSTEM

After a structural bay has been developed for each zone and sub-zone, the bays are inserted within the massing to create the building's structural system. This schematic structural drawing (Fig. 5.40) provides the architect with a comprehensive visual of the required structural density throughout the building. The architect can use this visual to design the building's interior and the exterior facade. Knowing the approximate spacing of columns and placement of bracing at this early design stage can inform program layout according to available space and potential for glazing. If larger member spacing would be beneficial in certain areas to create larger open spaces, the architect can test new bays with the FEA software, using the same iterative process to increase the column spacing, while also increasing member sizing or adding bracing to compensate for the longer spans. Once such a bay has been developed so that its deflection in the wind is acceptably low, these larger bays can be inserted where they are needed within the building. The architect can repeat this process as necessary until the structural and architectural designs work together, and neither compromises the other. This consideration of the building interior will be elaborated upon in the following chapter.

The intention of this part of the design method is for the architect to develop the structure to a point where they can see how it will impact the building design. By doing this structural layout in the initial design phases, the architect gets a realistic idea of what the structure needs to be, to make sure that no future design moves will compromise the approximate structure that they know has to be included. This method does not intend for the architect to replace the structural engineer. Instead, it equips the architect to design a building that can accommodate a feasible structural system, and develop a schematic structural design that the engineer can then easily size and detail. It provides a way for the architect to develop a qualitative understanding of wind loads and the structure required to resist them, to integrate into the initial building design and improve collaboration between the architect and the structural and wind engineers.

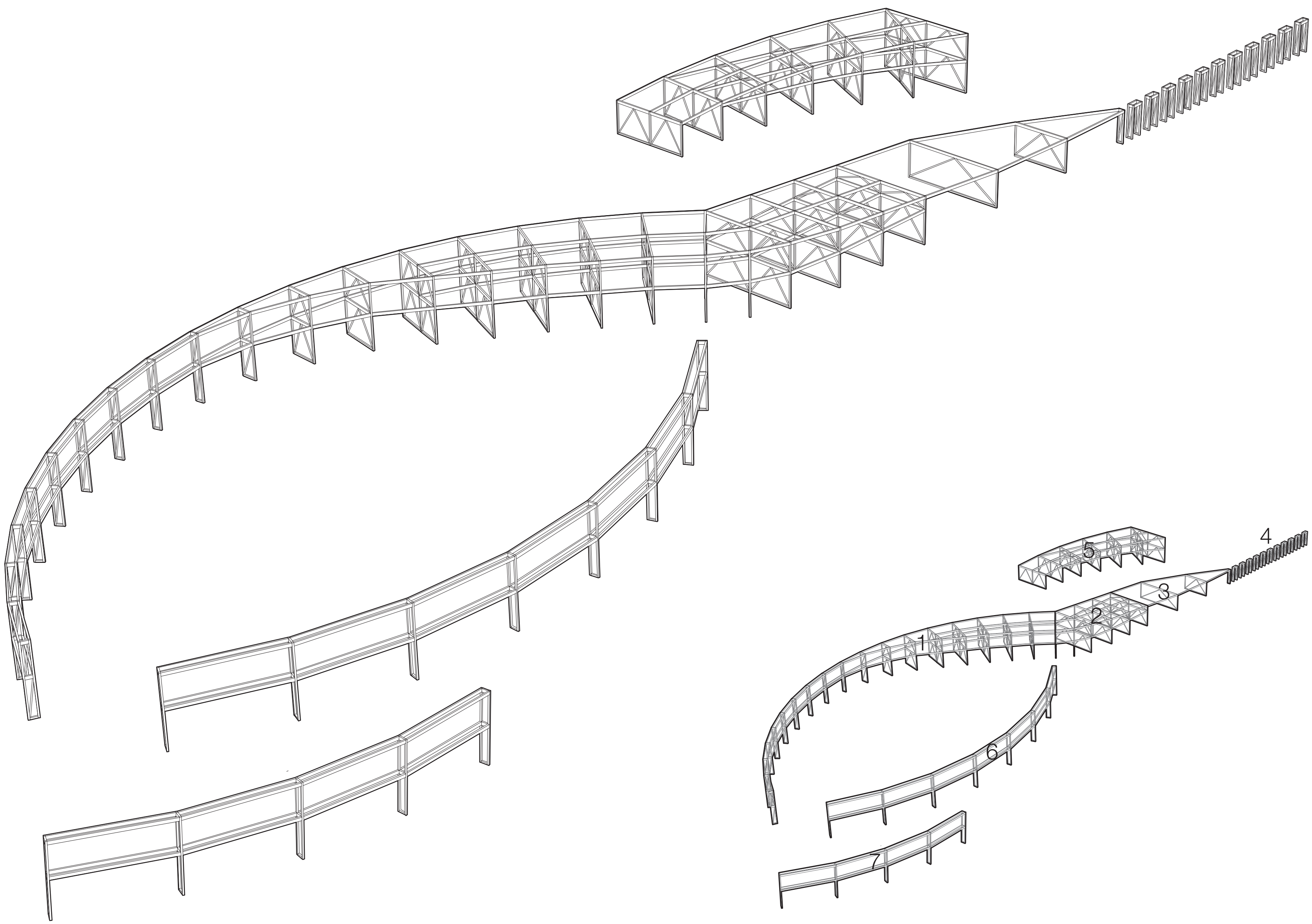


Fig. 5.40. Schematic structural drawing (left) and pressure zones overlaid onto structural drawing (right).

5. MODIFIED FORM

The form of the building (Fig. 5.41) can then be adjusted to reflect the inclusion of the steel structure (Fig. 5.42). For example, curved sections could be faceted, with each side length equal to the length of the column spacing. This modified form is then re-tested with Vasari to ensure that the change to the form did not undesirably alter the wind conditions around the building (Fig. 5.43, Fig. 5.44). If the wind conditions are found to have changed in certain areas, this would affect the wind pressure that is applied to that area of the building. A new pressure zone would be created and a new structural bay for that zone would be developed with the same iterative FEA process described in this chapter. If the wind conditions are altered so much as to become undesirable, the form itself would need to be adjusted so that it fosters the intended wind conditions, yet is also an appropriate shape to be able to accommodate a steel-frame structure. This step completes the feedback loop between the CFD and FEA programs. At this point, the design method may be repeated as many times as necessary to develop a building that both shapes and resists the wind, before the form is refined at a finer scale in the next and final step in the design method.

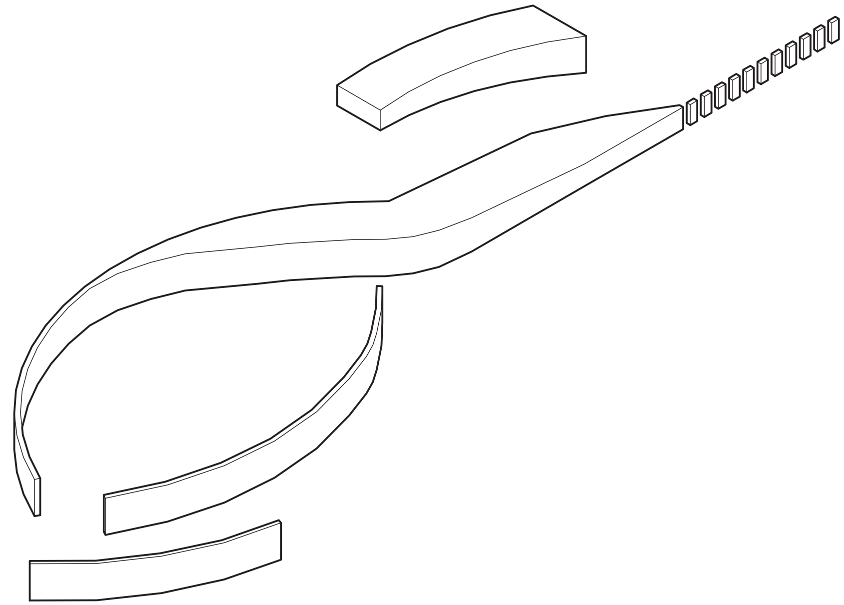


Fig. 5.41. Building form.

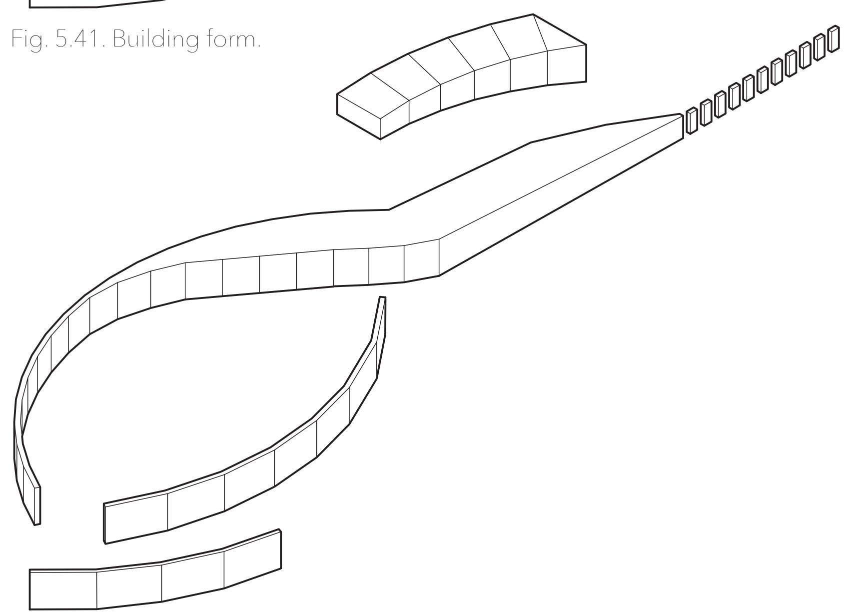


Fig. 5.42. Adjusted building form to reflect the inclusion of the steel structure.

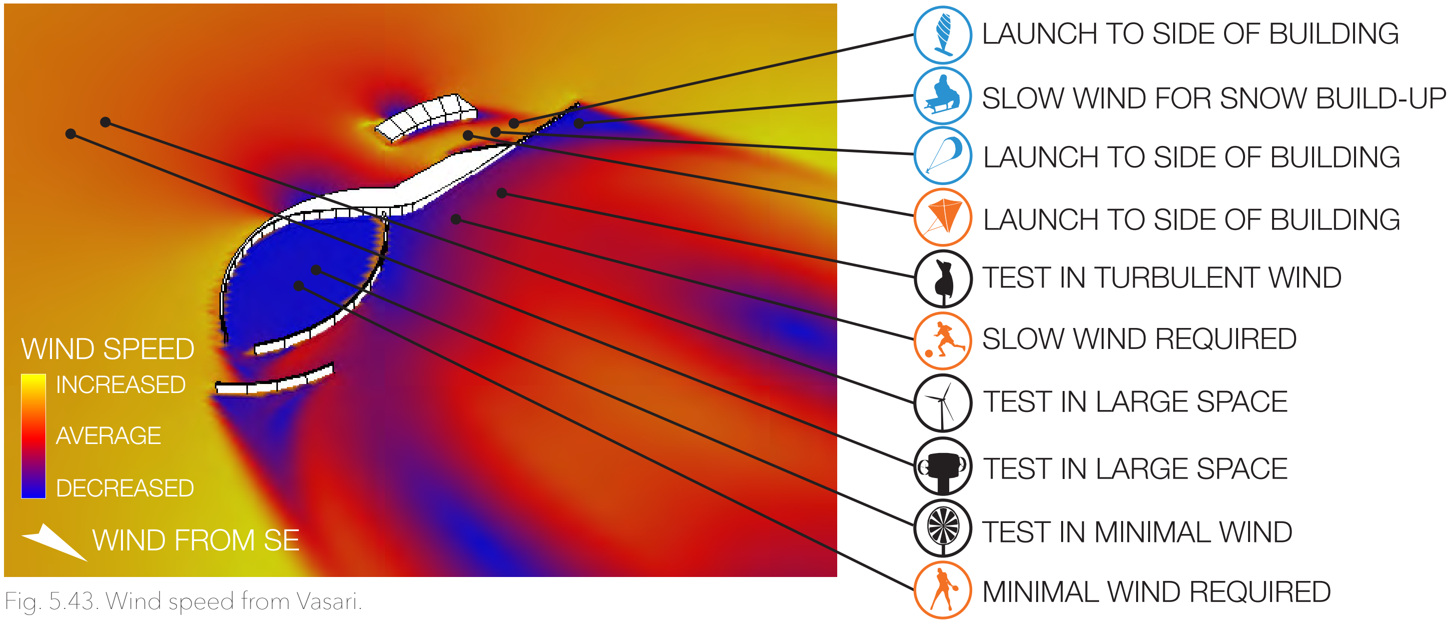


Fig. 5.43. Wind speed from Vasari.

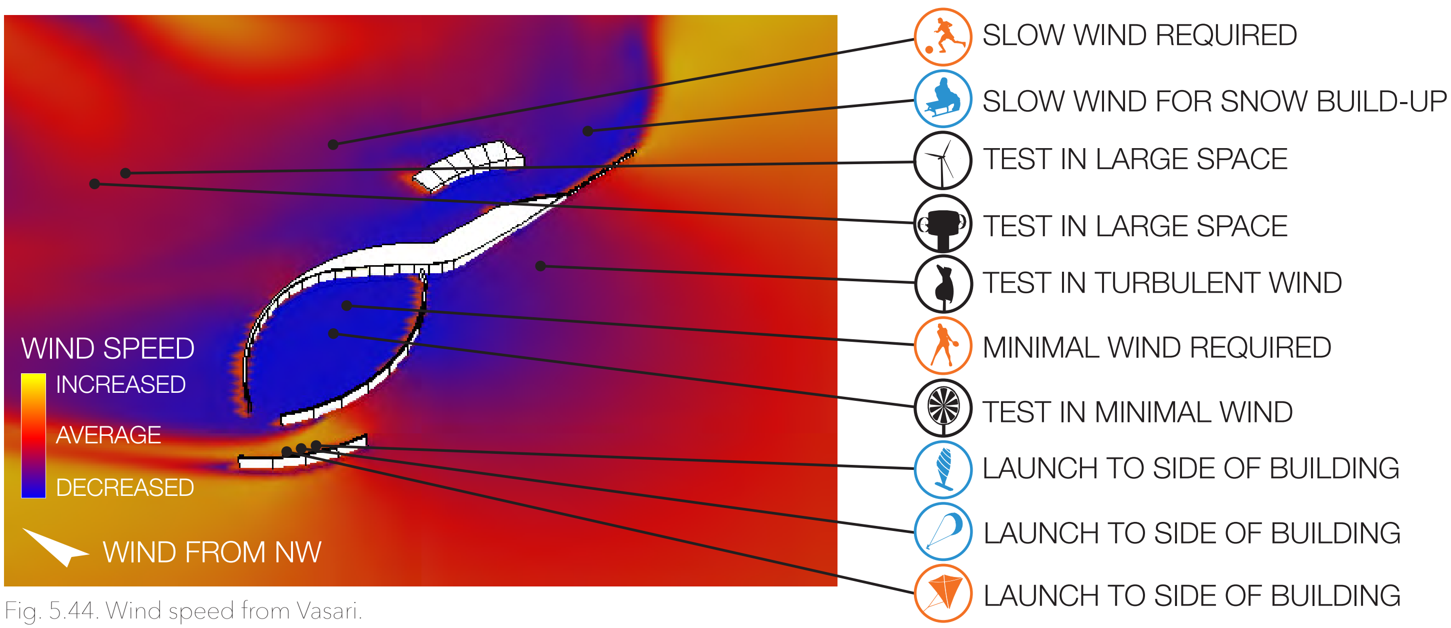


Fig. 5.44. Wind speed from Vasari.

PROGRAM AFFECTS FORM AND STRUCTURE

HOW PROGRAM AFFECTS FORM AND STRUCTURE

The steps of the methodology that were described in the previous chapters allow the architect to develop a building form that creates desirable wind conditions for a set of exterior programs while reducing and resisting the wind loads that are generated by these wind conditions. This may be achieved through one or multiple iterations of the methodology thus far. Now that the form has been established, it should be refined in this fourth and final step of the design method, so that it could feasibly be developed from a form into a building during a later design phase. The intent of this refinement is not to substantially alter the design, but to make small adjustments to the form and the structure so that it could be made into a building with both interior and exterior programs that would function within the site's wind conditions.

The following considerations should be made to refine the building form that was developed in the previous chapters:

INTERIOR PROGRAM

The form that was developed through the previous steps should be adjusted at a finer scale so that the interior program could feasibly be accommodated. Once the model is changed accordingly, it should be re-tested in Vasari to ensure that the adjustments to the form did not undesirably alter the surrounding wind conditions.

EXTERIOR PROGRAM ELEVATIONS

In previous chapters, the building form was developed based on the wind conditions at a single elevation close to the ground level. However, some of the exterior programs would occur at other vertical elevations. The wind conditions around the building form should therefore be tested in Vasari at all of the elevations at which these programs would occur, to ensure that the wind conditions are appropriate for the exterior programs.

REFINEMENT OF STRUCTURE FOR FORM AND PROGRAM

The layout of the structural bays should be adjusted to fit within the new building form and to accommodate the interior program. The structure may be made into a prominent feature of the architecture.

INTERIOR PROGRAM

Although detailed interior building layouts are not a part of this design method, the building form that has been developed should be able to feasibly accommodate the required interior programs. This may be achieved through minor modifications to the building form. The purpose of the building that is developed through this methodology is to alter the wind patterns around the building to create appropriate wind conditions for the exterior programs, and to provide interior space to support these exterior programs. As such, the interior program requirements are minimal, and only serve to support the wind energy generation technologies and exterior sporting activities that exist within the wind conditions that it is the building's primary purpose to create. For the next step in the refinement of the building, modifications to the building form were made to accommodate these interior programs. Then, the adjusted form was tested in Vasari, simulating wind coming from both of the site's predominant wind directions to ensure that the small adjustments to the form did not alter the appropriateness of the wind conditions for the exterior programs.

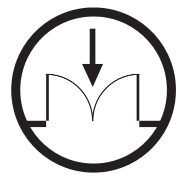
The following interior programs were accommodated through slight modifications to the building's form (Fig. 6.1) that allow the form to feasibly be made into a building (Fig. 6.2) that accommodates the exterior programs within both predominant wind directions (Fig. 6.3-Fig. 6.6):

INTERIOR SPECTATOR AREA
This area used to be a wall with the sole purpose of sheltering the courtyard space, but its width was increased to 5m to accommodate an interior spectator area. This space has sliding glass doors on both sides so that visitors to the building can easily access the exterior, or remain inside and look out towards the activities happening on either side. It needed to be 9m high to adequately shelter the adjacent spaces from the wind, so this area may be a double-height feature space within the building.

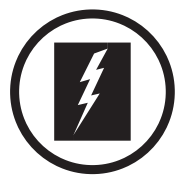
EXTERIOR SPECTATOR STANDS
Stands were added to the two freestanding walls that were initially made part of the form to create a sheltered courtyard and a channel of high-speed wind. These walls that were previously only included to shape the wind around the building now also serve a programmatic purpose. Stands were also added to one side of the smaller building form. These exterior stands provide space for spectators to observe the sporting areas that cannot be viewed from the interior spectator area.

CHANGE ROOMS
Change rooms have been added towards the south end of the building. This part of the building only needs to be a single storey high to generate the desired wind conditions in that area, so it is logical to use this space to accommodate back-of-house programs such as change rooms.

EQUIPMENT STORAGE
The equipment storage is located next to the change rooms, at the south end of the building. Like the change rooms, only a single storey is required for this program, so it may be included in this area.

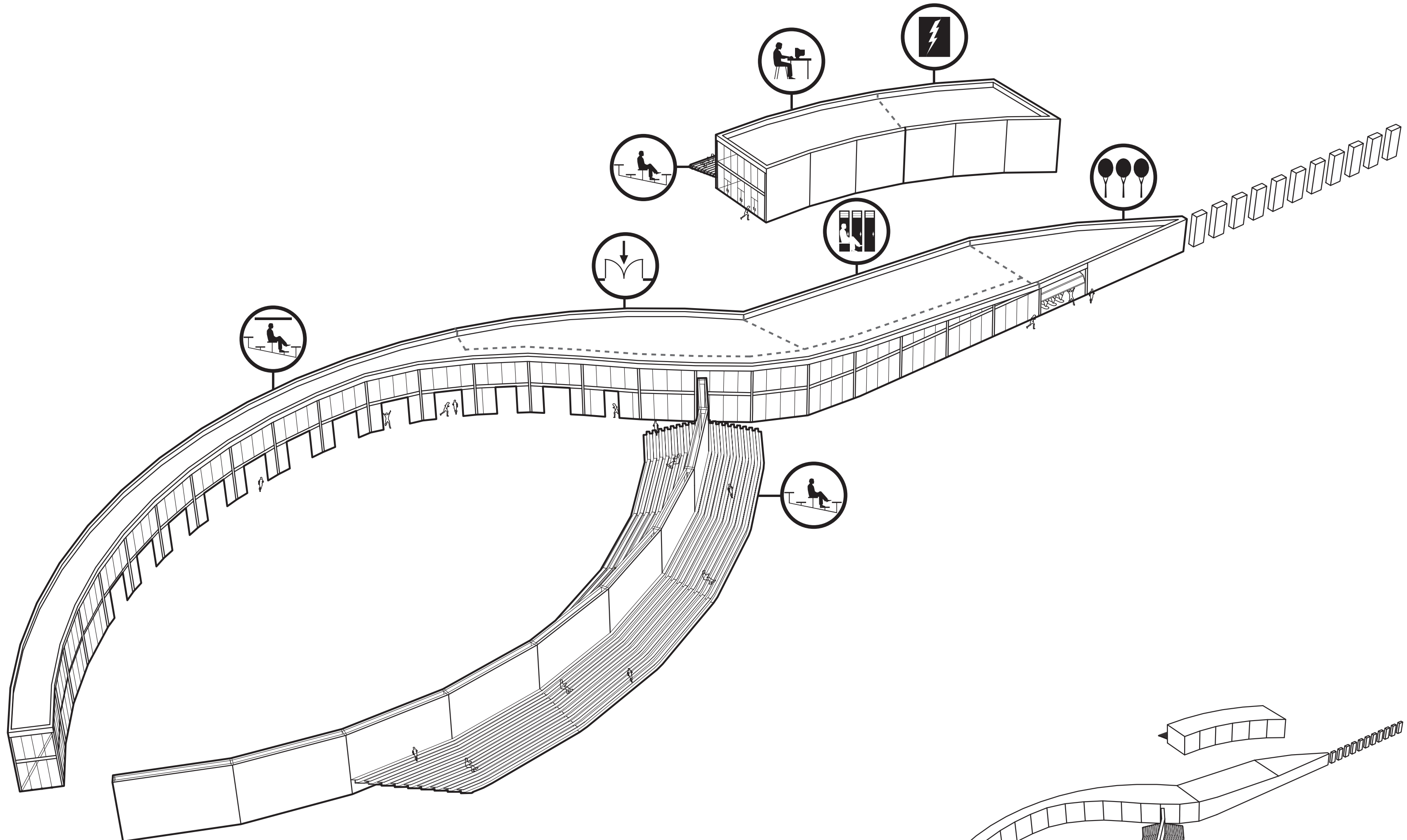


ENTRANCE
The entrance to the building is located between the change rooms and interior spectator area, for easy access by visitors who are either players or spectators of the exterior sports activities.



ENERGY STORAGE
The energy that is generated by the wind energy generation technologies is stored in the smaller building volume. The volume height was increased to two storeys to accommodate the large energy storage equipment.

OFFICE
Office space is also located inside the smaller building volume. This space would be used to study and compare data from the energy generation technologies, so that the site may be used as an energy testing and experimentation facility as well as a community sports facility.



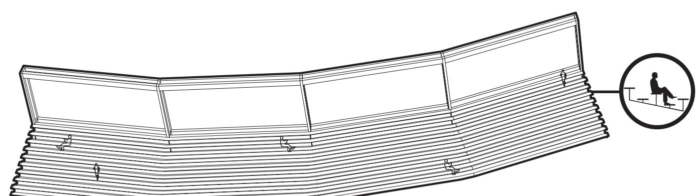


Fig. 6.2. Building with program.

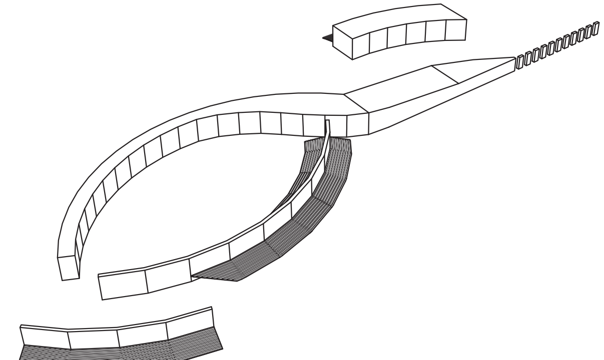


Fig. 6.1. Building form.

WIND FROM SE | SUMMER

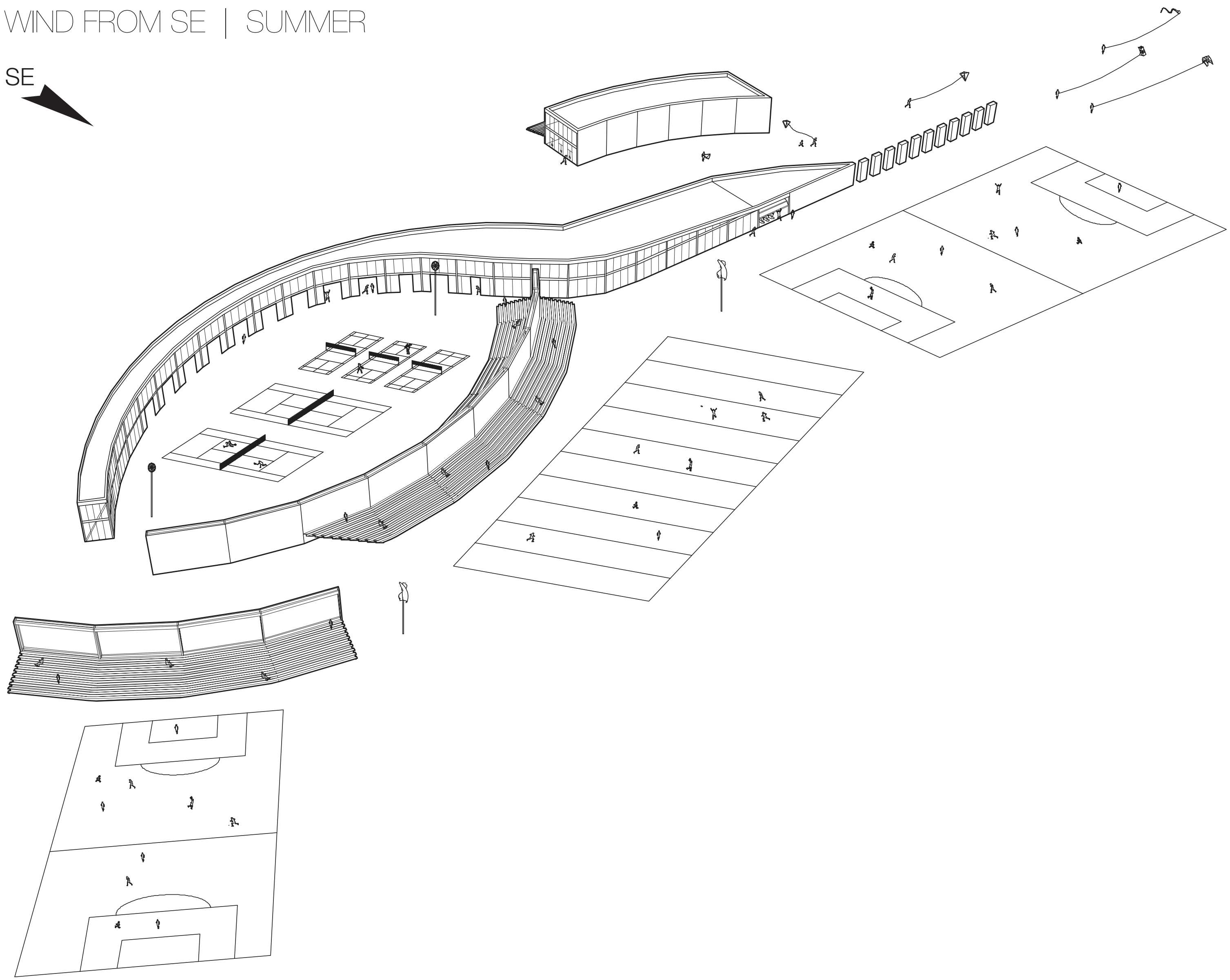


Fig. 6.3. Building and exterior programs when wind blows from the SE in summer.

WIND FROM SE | WINTER

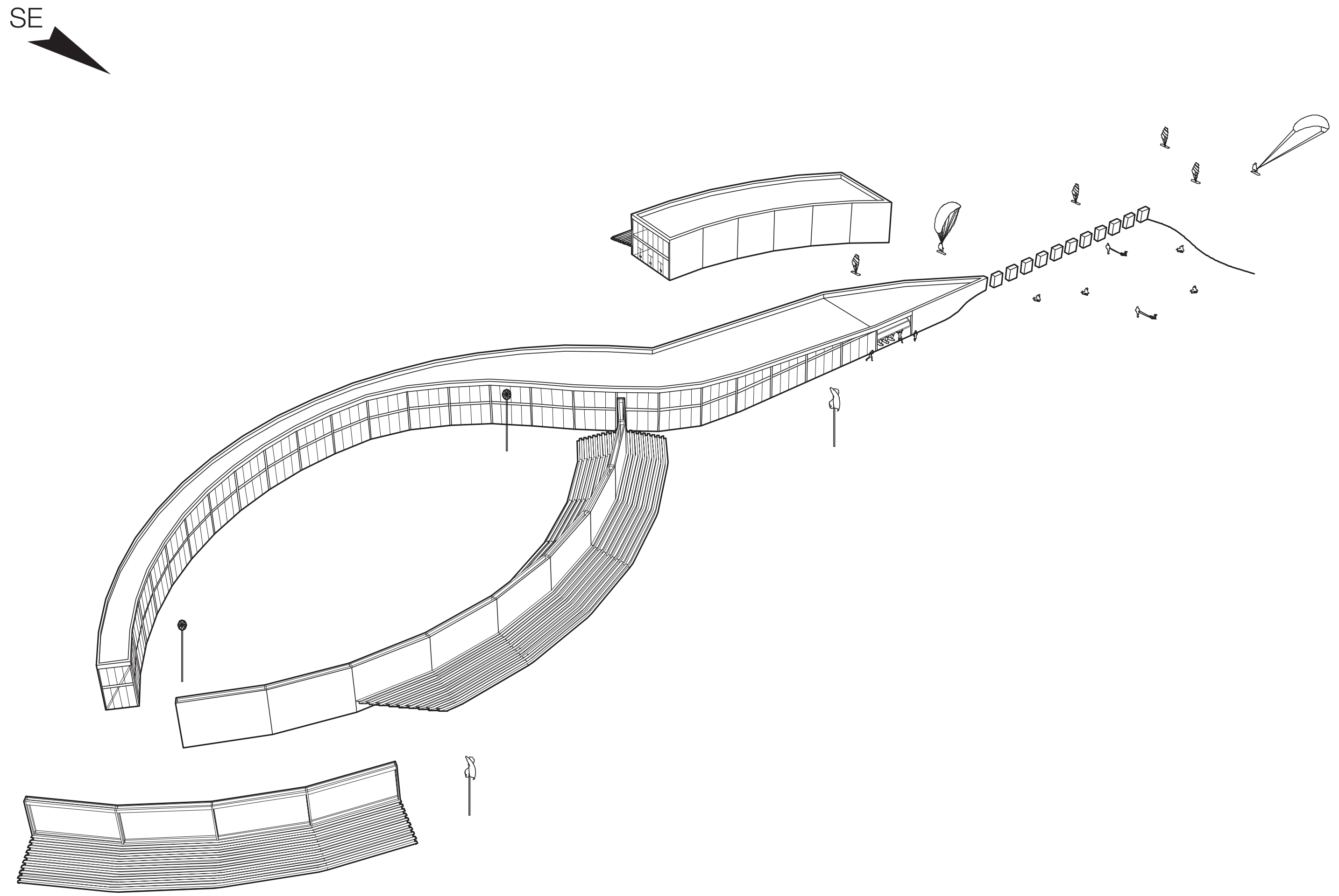


Fig. 6.4. Building and exterior programs when wind blows from the SE in winter.

WIND FROM NW | SUMMER

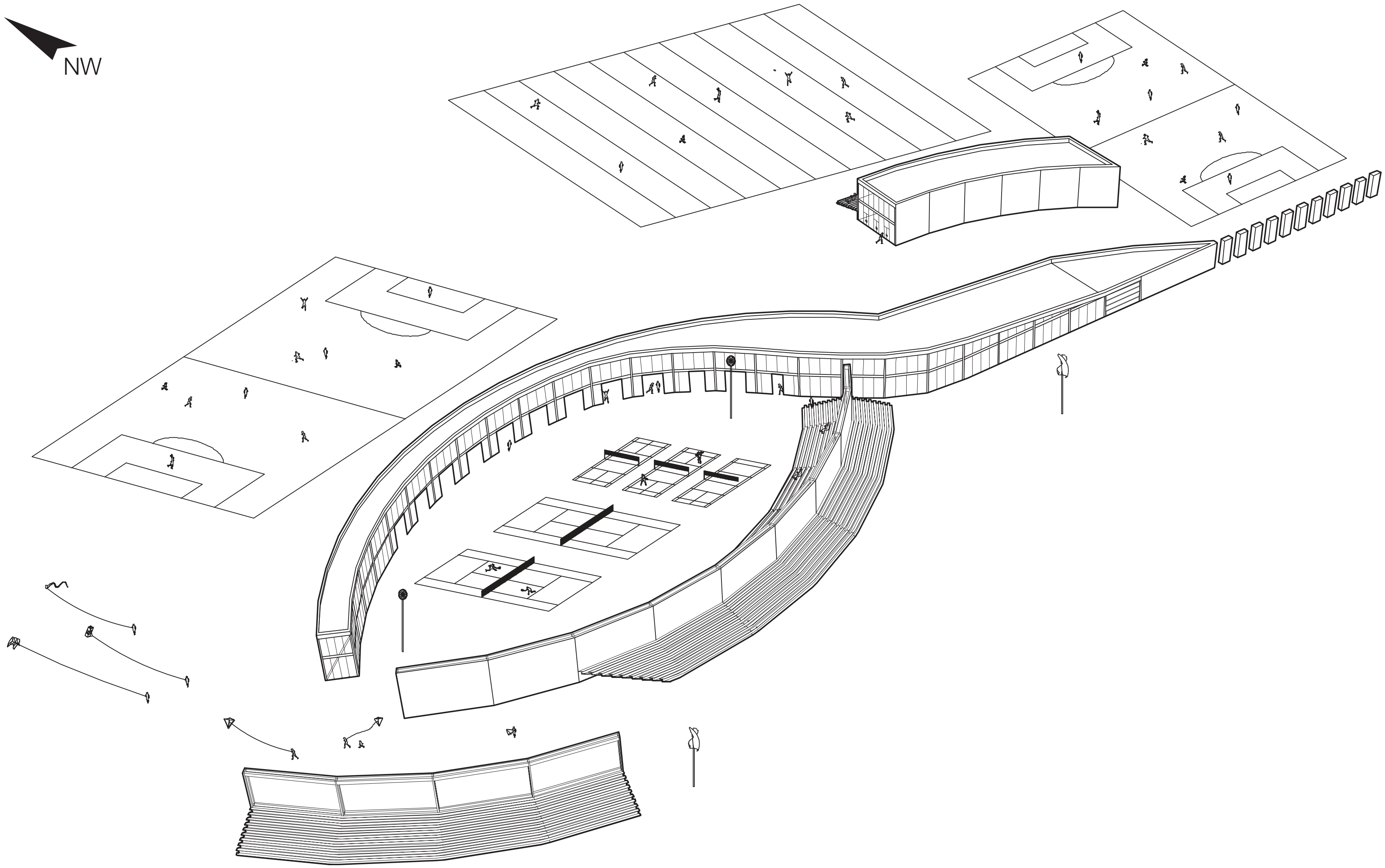


Fig. 6.5. Building and exterior programs when wind blows from the NW in summer.

WIND FROM NW | WINTER

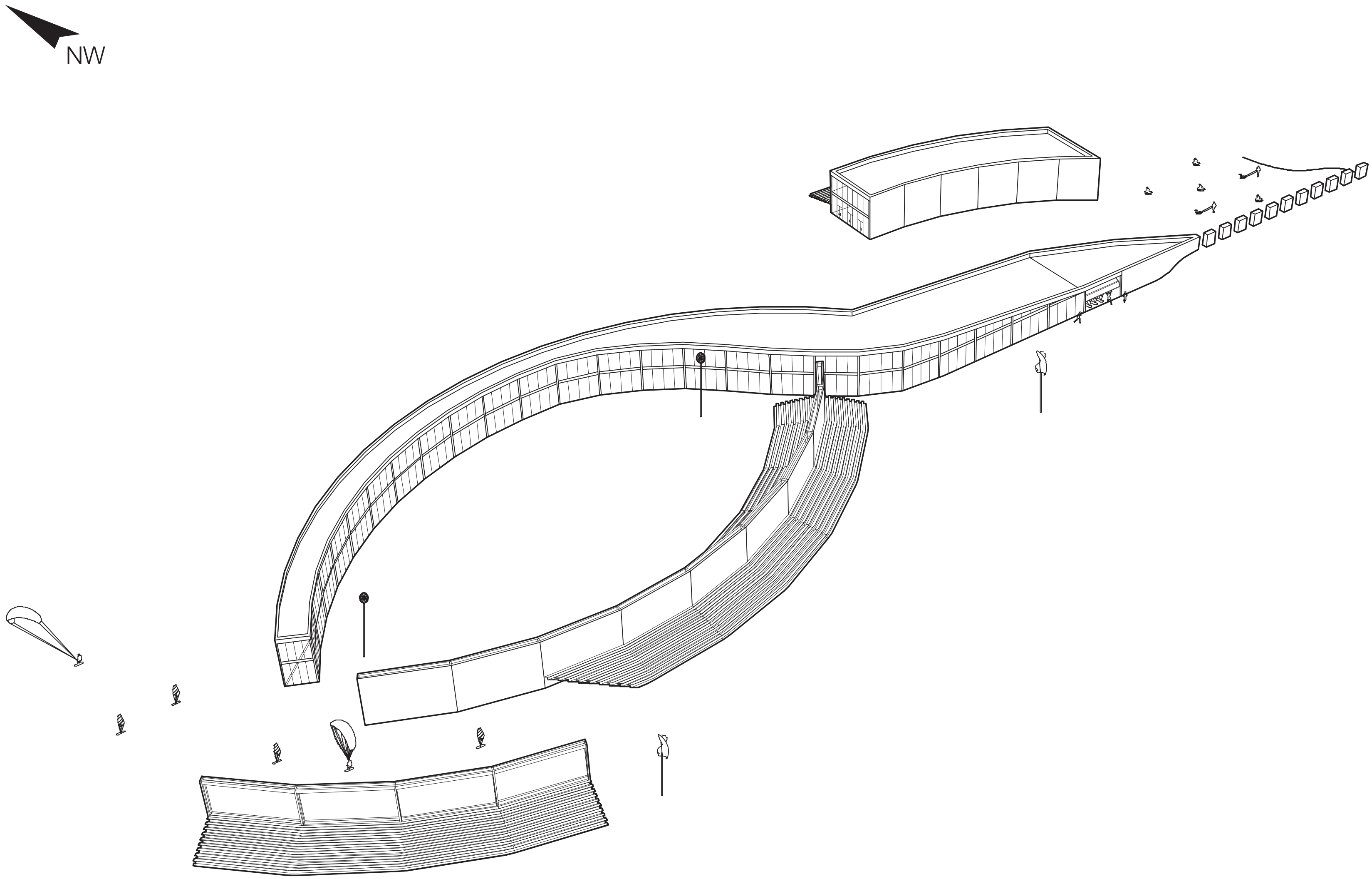


Fig. 6.6. Building and exterior programs when wind blows from the NW in winter.

CFD SIMULATION

The modified form was tested in Vasari with wind simulated from both predominant directions (Fig. 6.7, Fig. 6.8), to ensure that the changes to the form did not undesirably alter the wind conditions for the exterior programs.

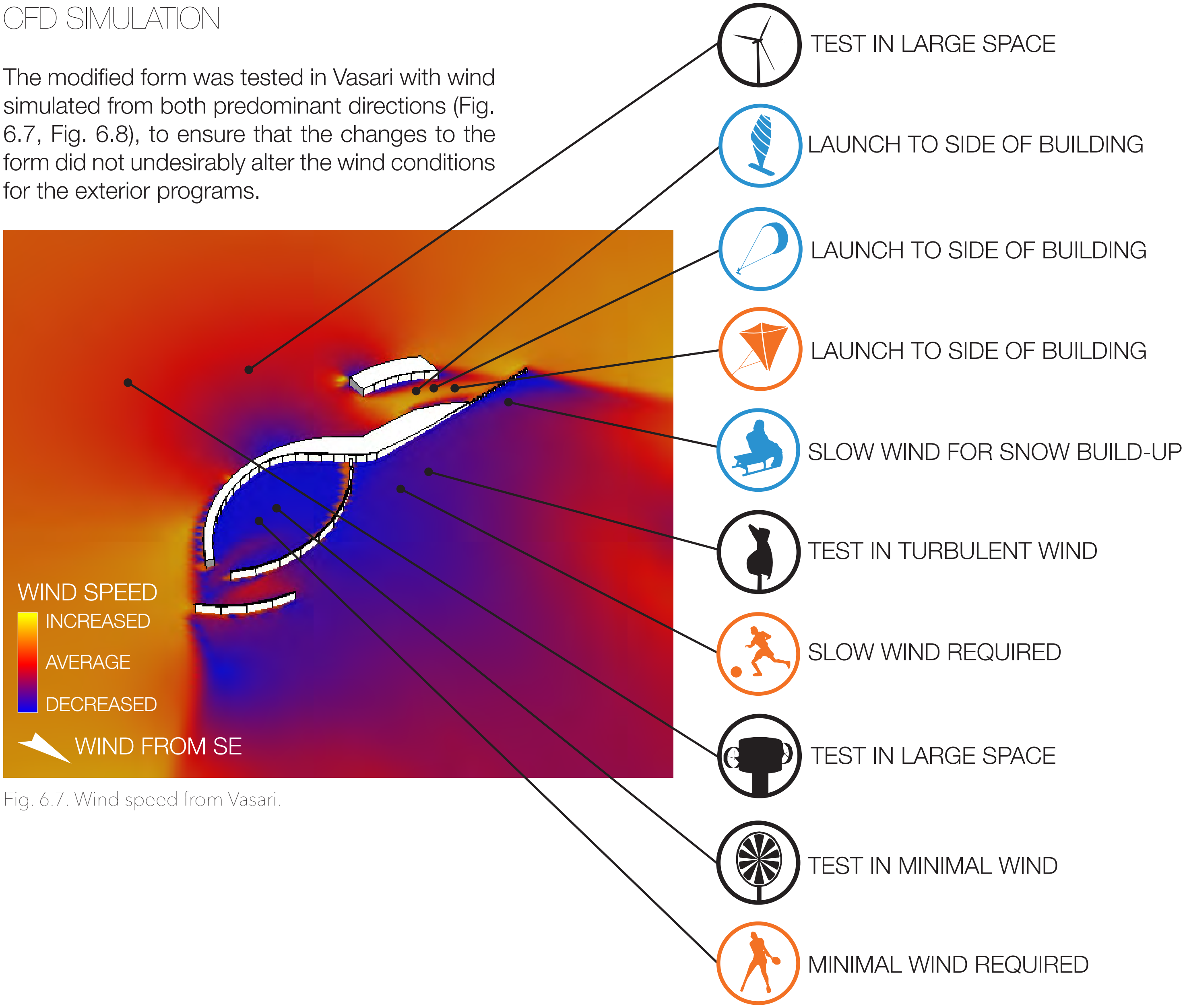


Fig. 6.7. Wind speed from Vasari.

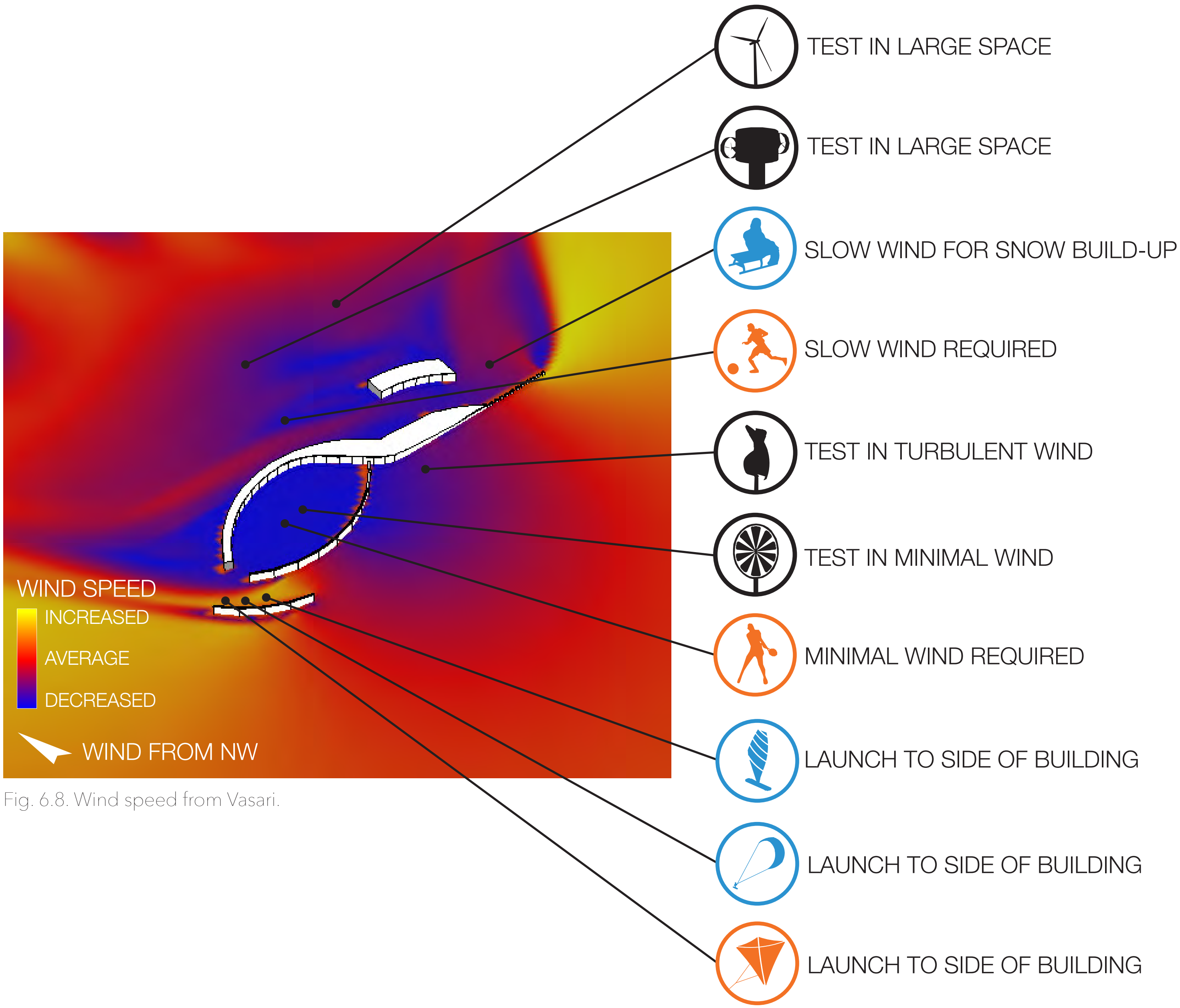


Fig. 6.8. Wind speed from Vasari.

EXTERIOR PROGRAM ELEVATIONS

Although the initial building form was developed based on the wind conditions that would be created around the building at a single vertical elevation, the exterior programs would actually occur at a variety of vertical elevations. For example, kites would be launched at ground level and therefore would require high-speed wind just above the ground in the kite-launching area, but because kites are flown at higher elevations, the open space for kite-flying would need to have fast winds higher up. To account for the wind conditions at different elevations in the design of the building form, wind speed data slices were taken in Vasari at each of the elevations at which the programs would occur, to ensure that the sports and energy generation technologies would be able to function properly at these elevations. The following Vasari data slices show that appropriate wind conditions are created for all of the exterior programs at their respective elevations. It should be noted that Vasari does not simulate the increase in wind speed as elevation increases, so any data slice that is completely above the building only displays the uniform input wind speed. However, as CFD programs improve, they may be able to depict accurate wind speeds at elevations above the building. This accuracy would make these results more useful in determining whether or not there are appropriate wind conditions for all of the exterior programs at all of the required elevations.

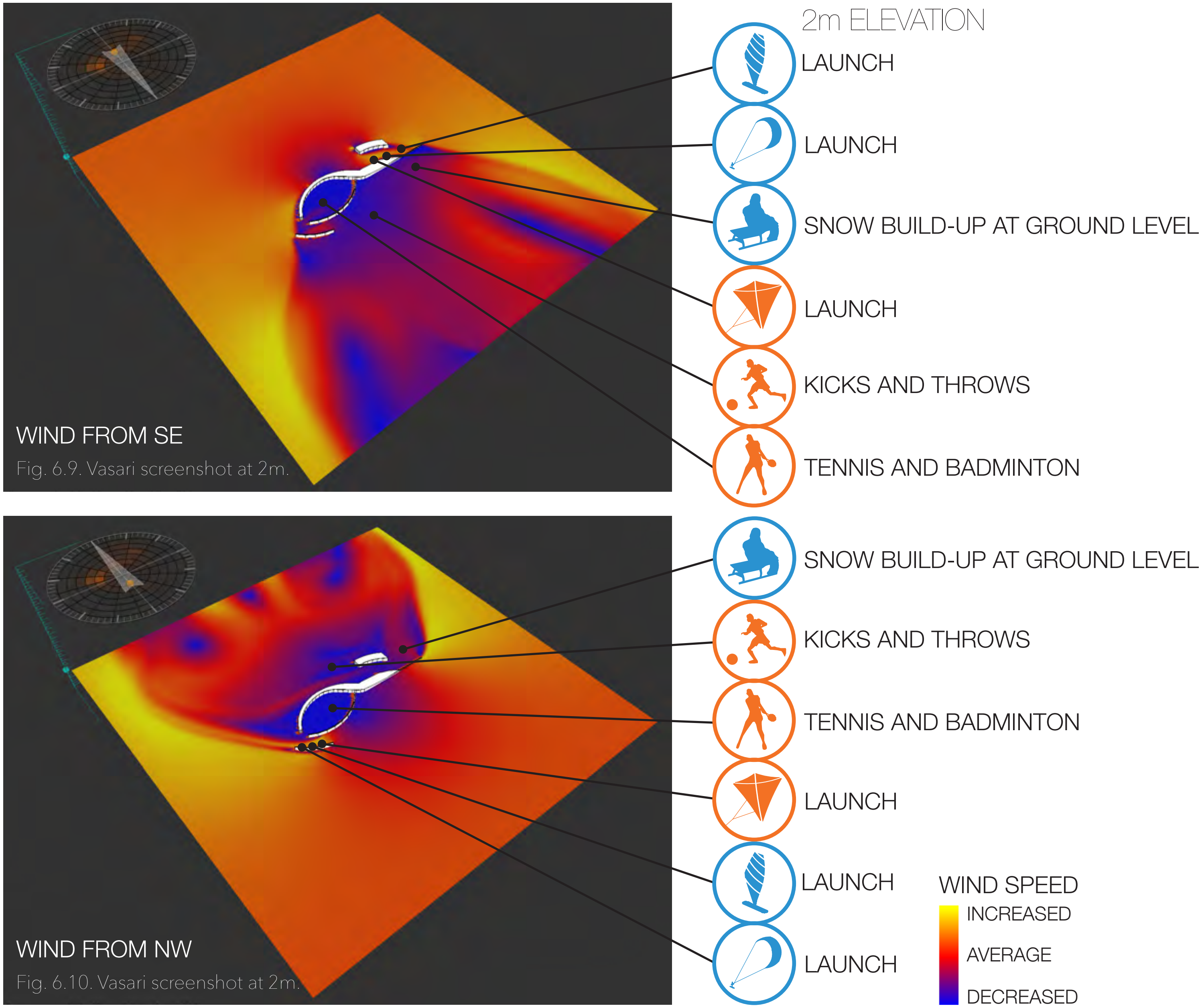


Fig. 6.9. Vasari screenshot at 2m.

Fig. 6.10. Vasari screenshot at 2m.

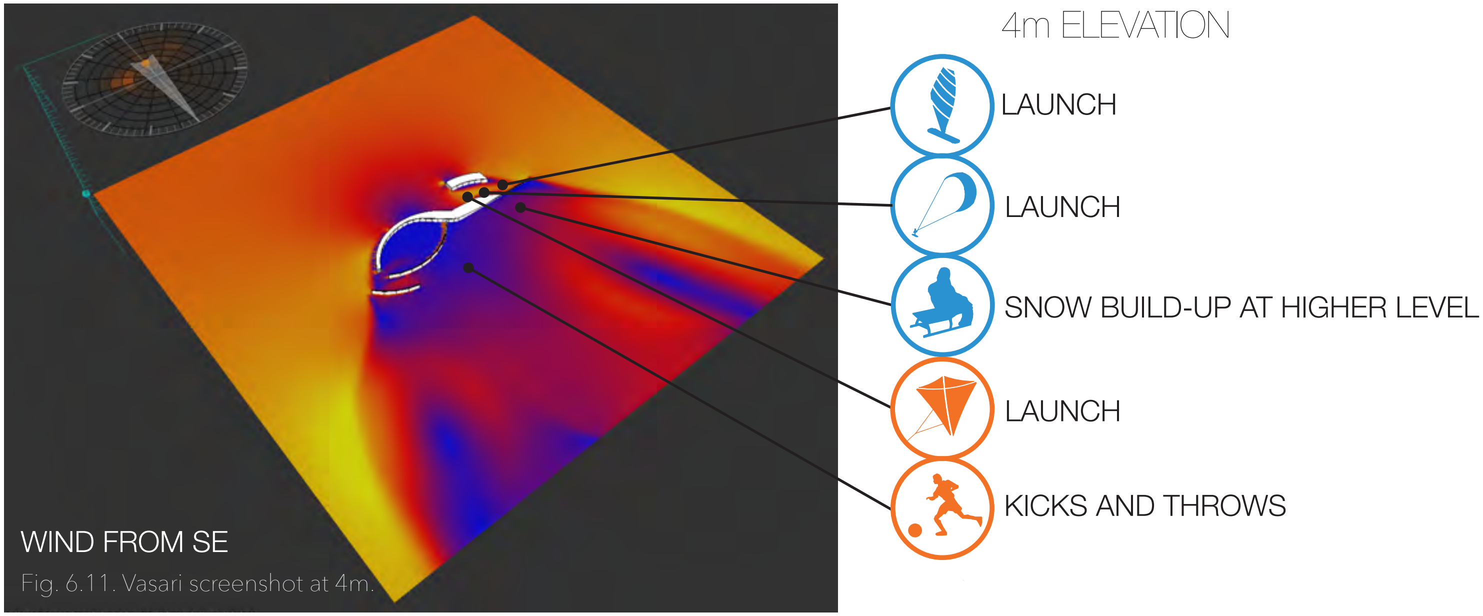


Fig. 6.11. Vasari screenshot at 4m.

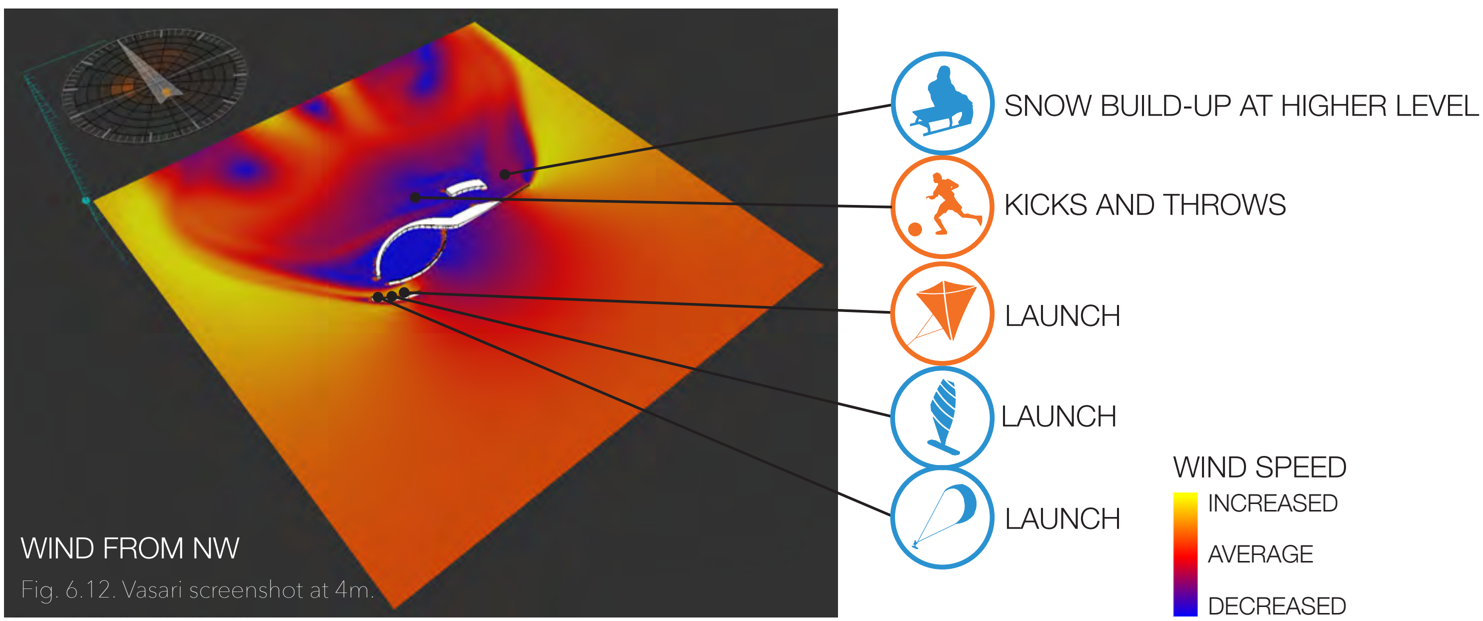
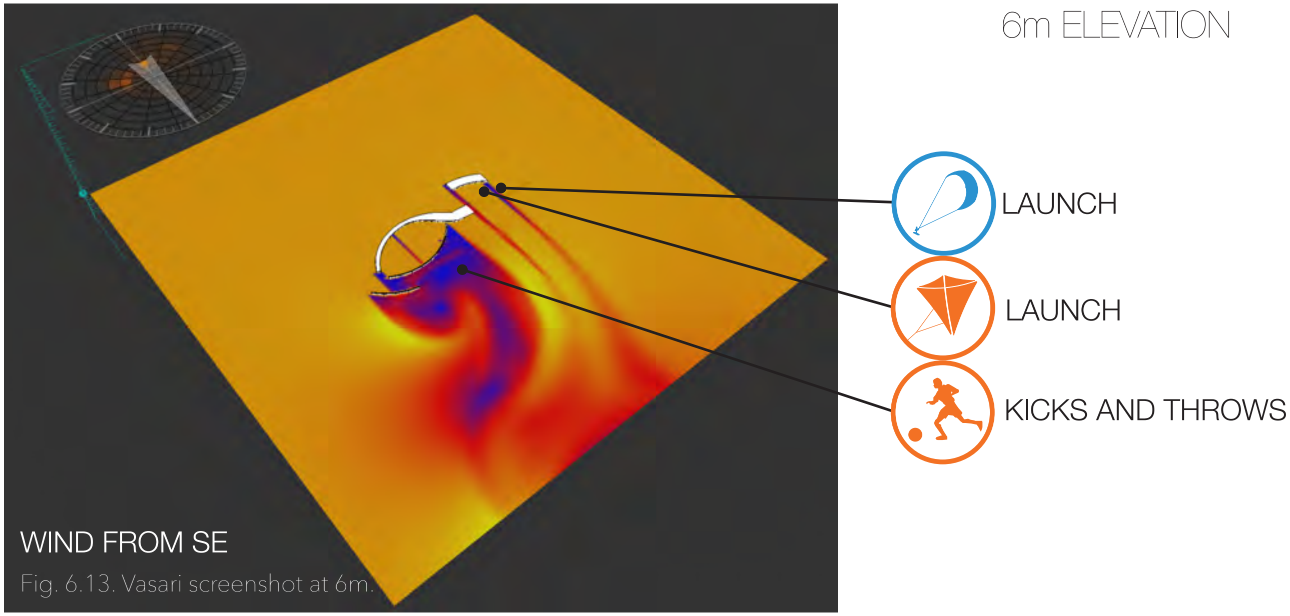
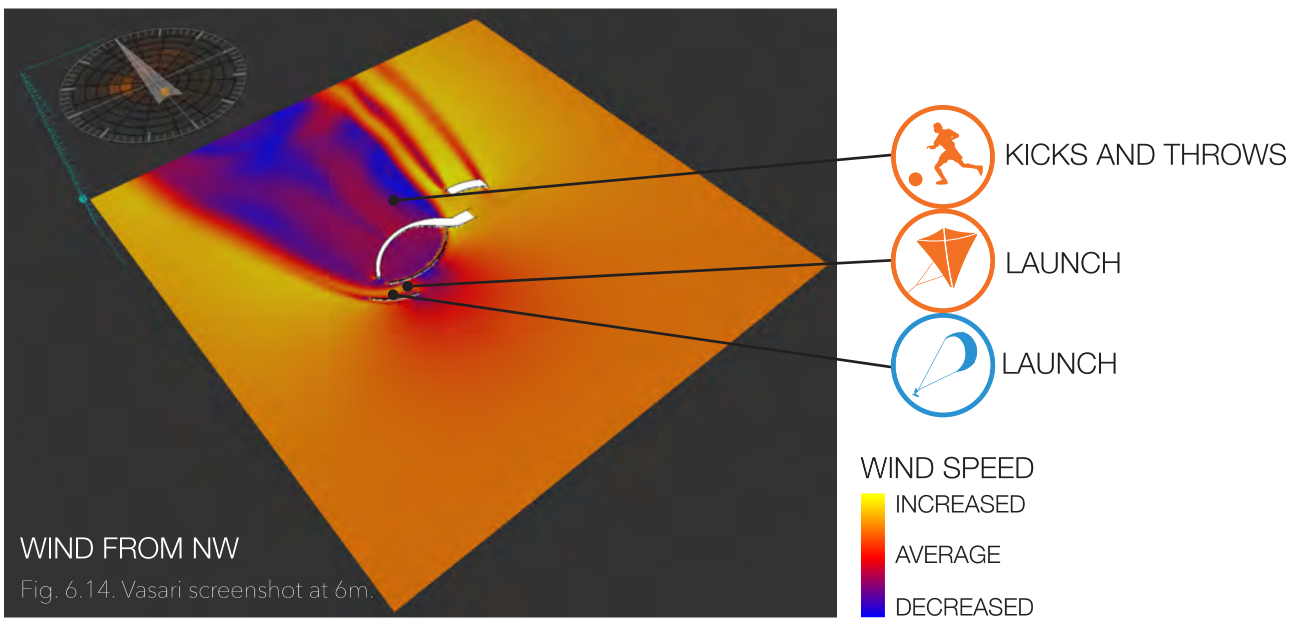


Fig. 6.12. Vasari screenshot at 4m.

6m ELEVATION



WIND FROM SE
Fig. 6.13. Vasari screenshot at 6m.



WIND FROM NW
Fig. 6.14. Vasari screenshot at 6m.

8m ELEVATION

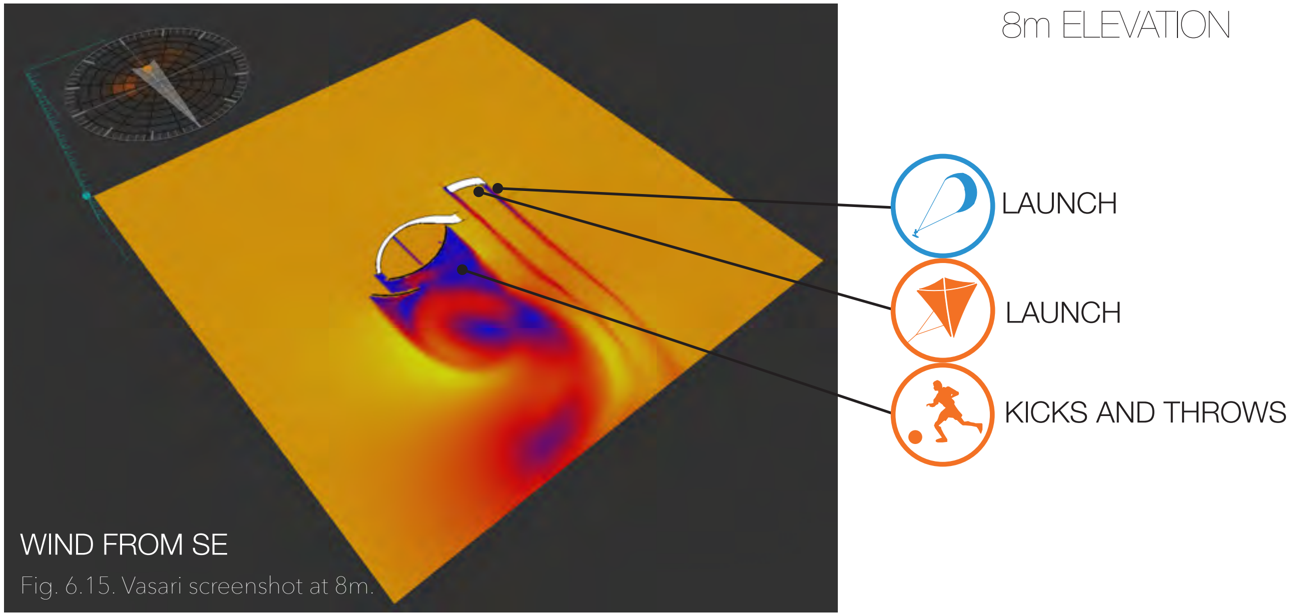


Fig. 6.15. Vasari screenshot at 8m.

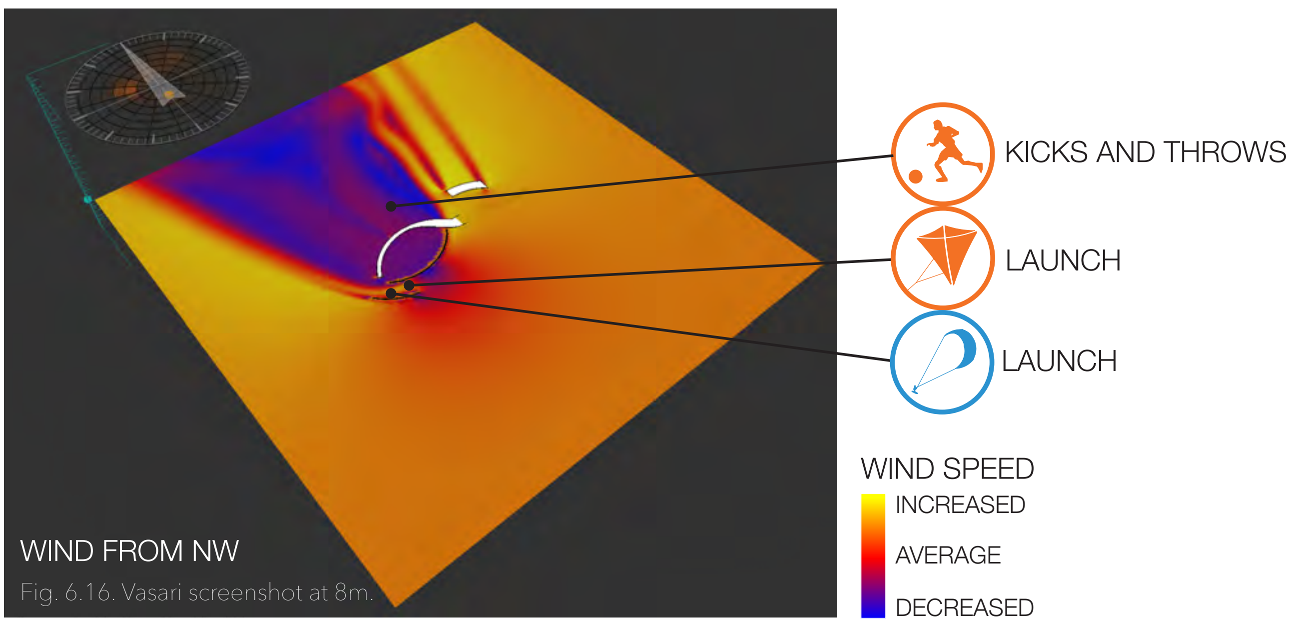


Fig. 6.16. Vasari screenshot at 8m.

10m ELEVATION

WIND ABOVE BUILDING NOT SHOWN IN VASARI

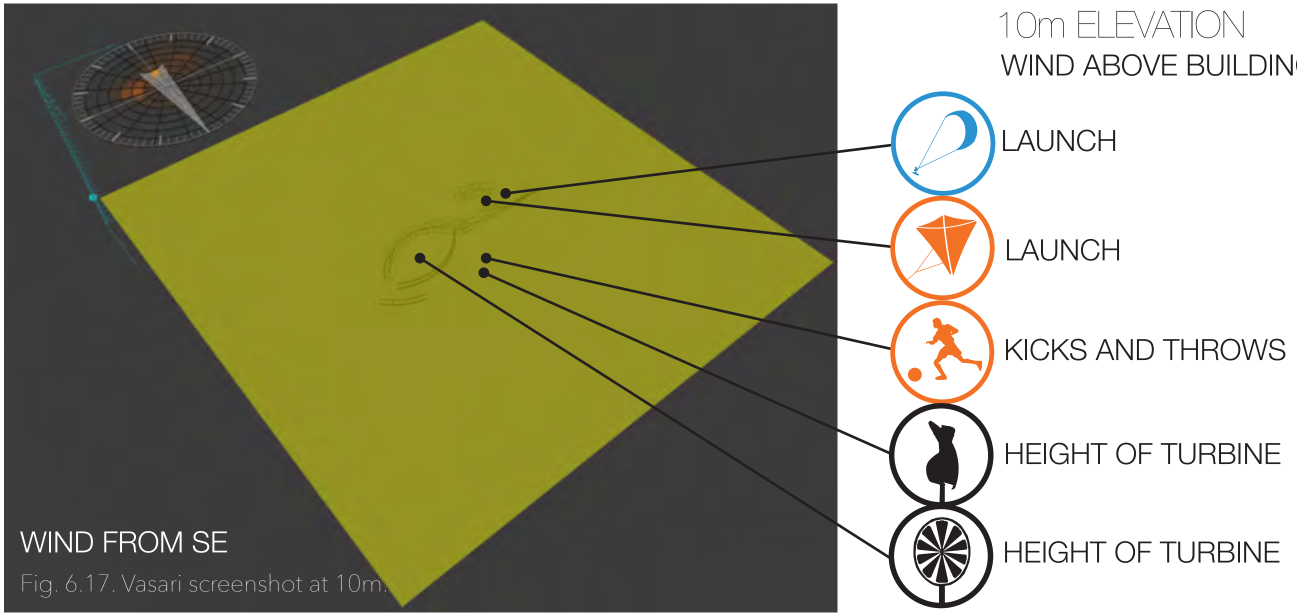


Fig. 6.17. Vasari screenshot at 10m.

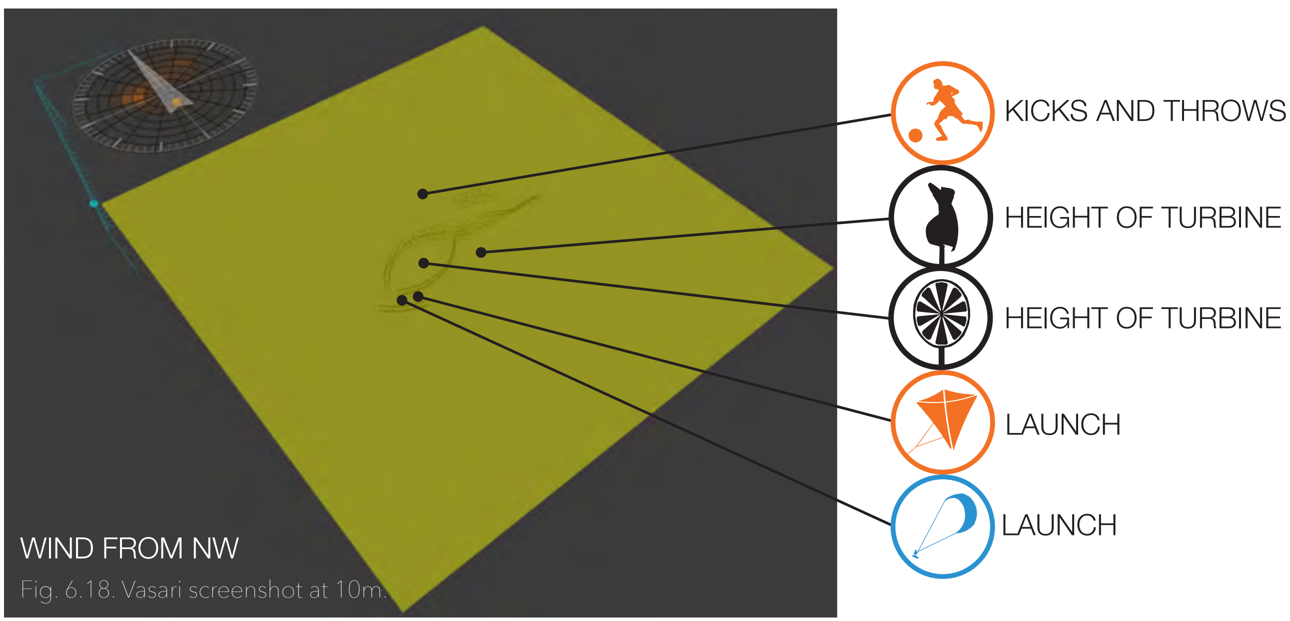


Fig. 6.18. Vasari screenshot at 10m.

20m ELEVATION

WIND ABOVE BUILDING NOT SHOWN IN VASARI

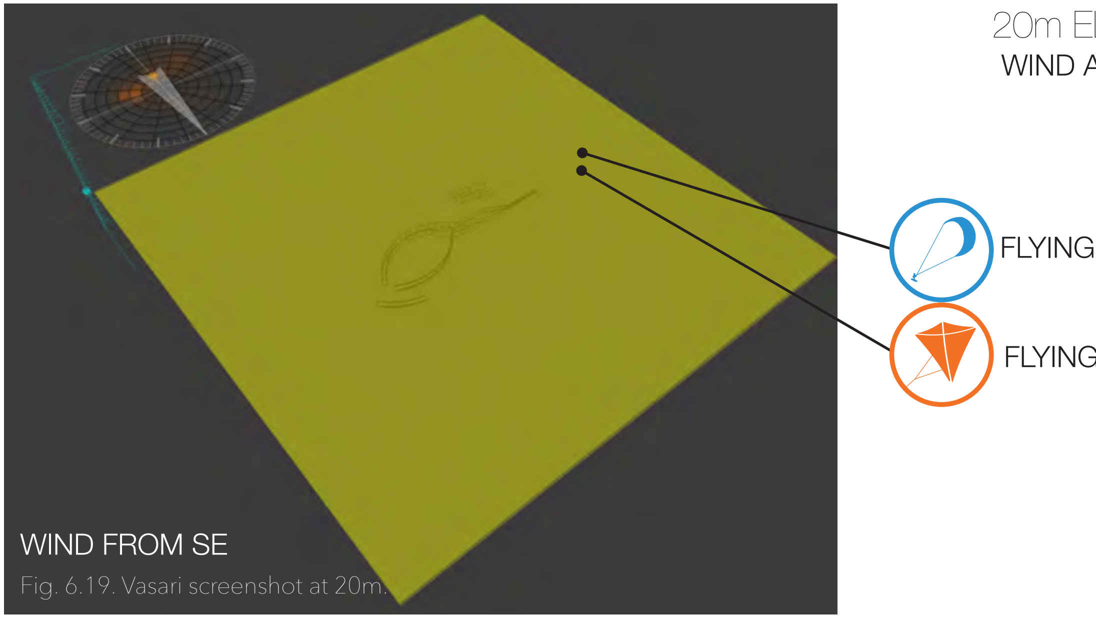


Fig. 6.19. Vasari screenshot at 20m.

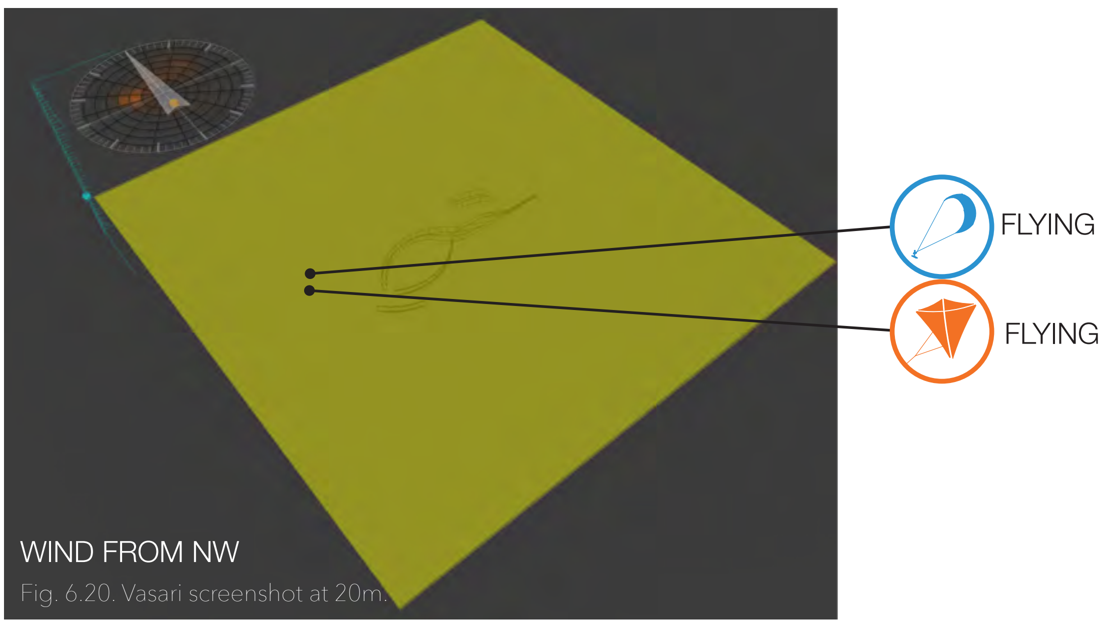


Fig. 6.20. Vasari screenshot at 20m.

60m ELEVATION

WIND ABOVE BUILDING NOT SHOWN IN VASARI

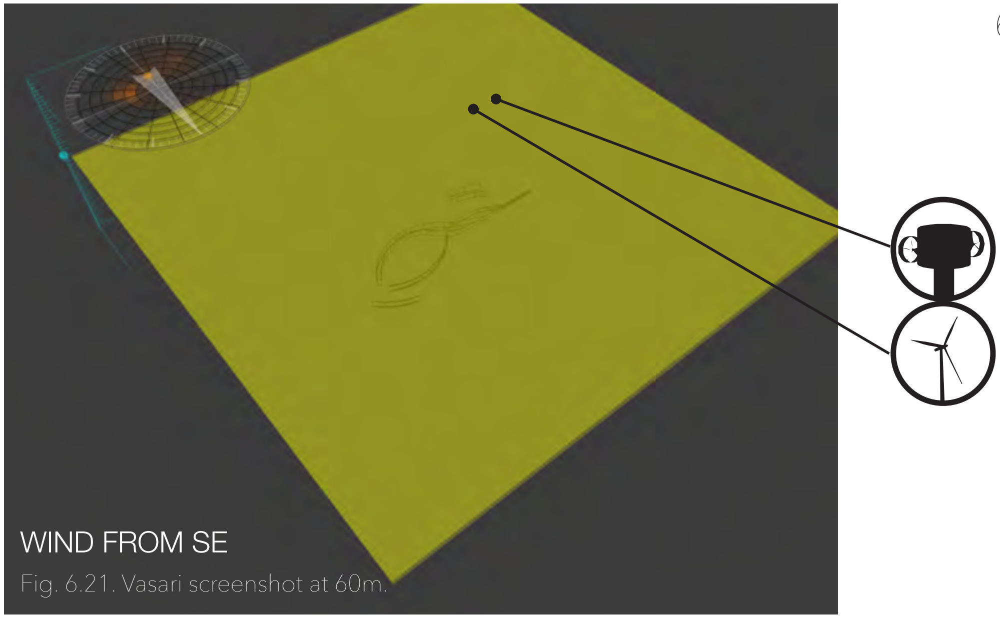


Fig. 6.21. Vasari screenshot at 60m.

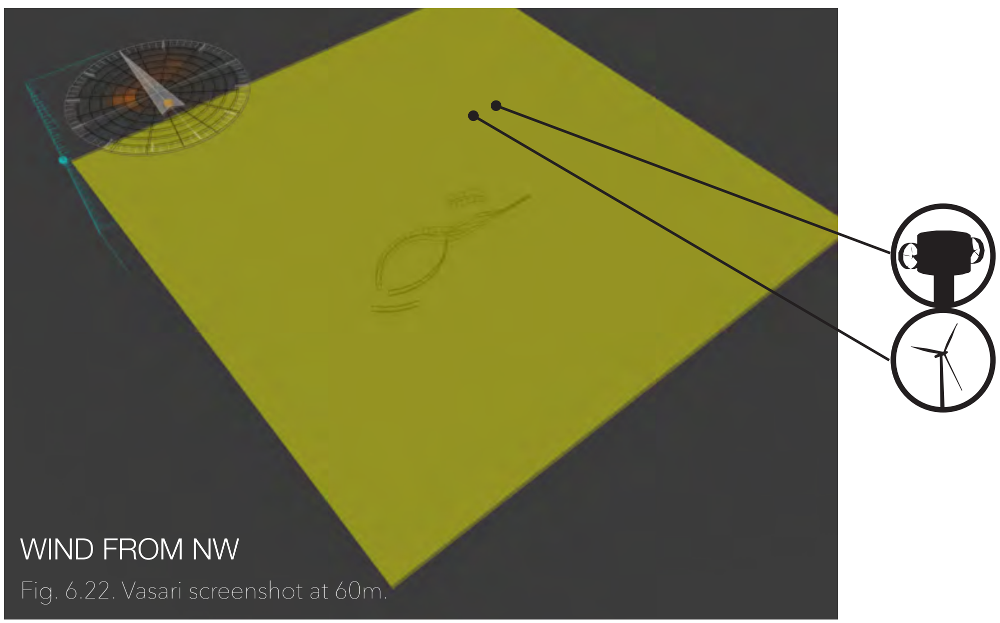


Fig. 6.22. Vasari screenshot at 60m.

REFINEMENT OF STRUCTURE FOR FORM AND PROGRAM

The last step in the refinement of the building is to co-ordinate the form, program and structure. The structural bays may be adjusted to fit within the refined form and to accommodate the interior program. Required alterations to the structure to accommodate these considerations could include changes to floor-to-floor heights, number of floors, or desired column spacing for the interior spaces. At this point, the structure may be made into a prominent feature of the architecture, as it may impact the use or aesthetic of the space. The final structural layout that fits within the building form and accommodates the interior program is shown in Fig. 6.23.

The interaction between the building form, the program, and the structure is shown in the section in Fig. 6.24. This sectional study informed the decision to clad the freestanding wall with perforated panels. The perforations alleviate some of the suction within the courtyard, while still slowing down the wind when it comes from the other direction to continue to shelter the courtyard.[1] The sizes of the perforations transition from large at the ends of the courtyard, to small in the middle of the wall. Without the perforations, a considerable amount of wind could enter the courtyard through the narrow openings at either end when the wind comes from the northwest.[2] The gradual transition in perforation size means that there are no longer only two small openings through which substantial winds could blow. This reduces the amount of wind that enters the courtyard.[3]

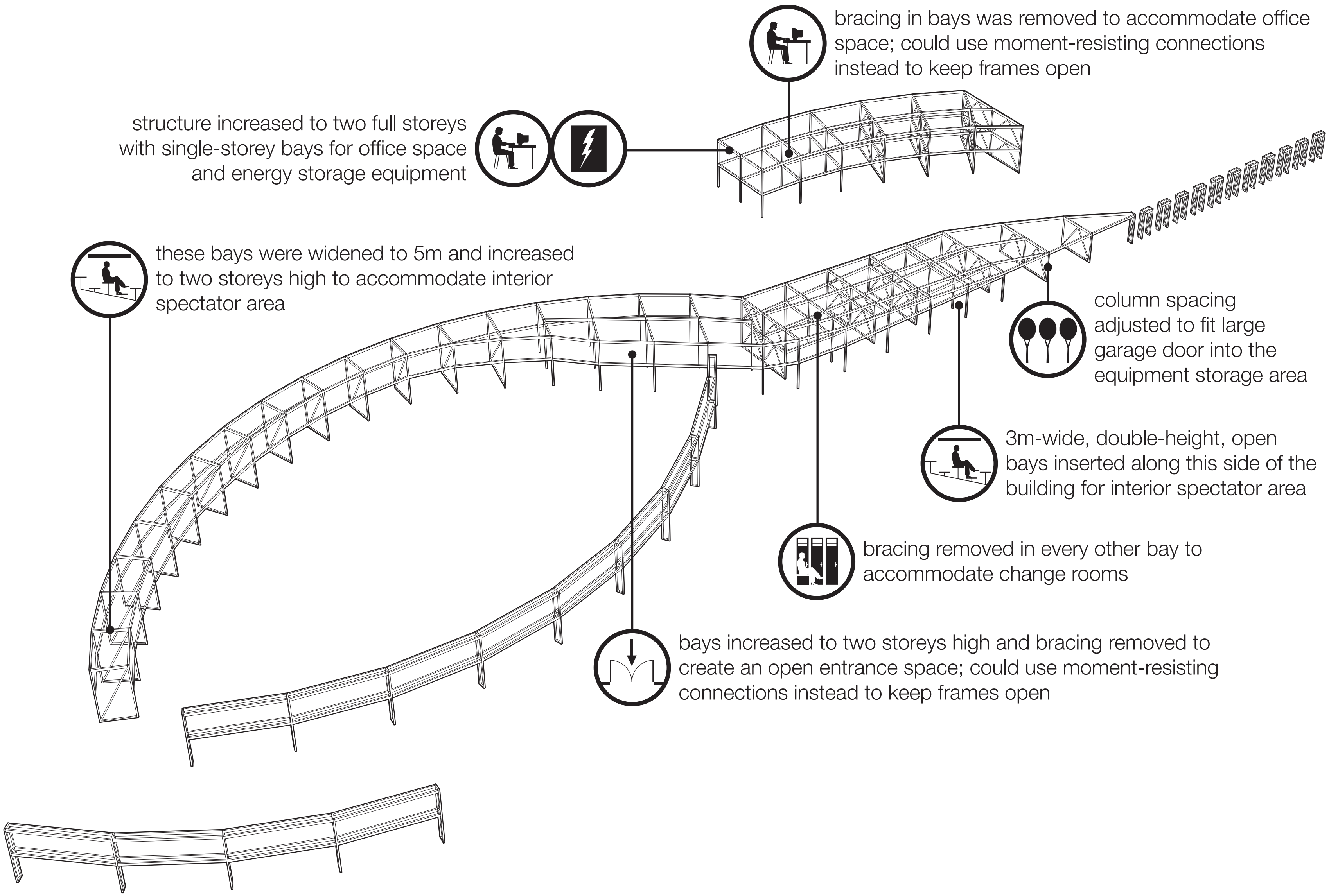
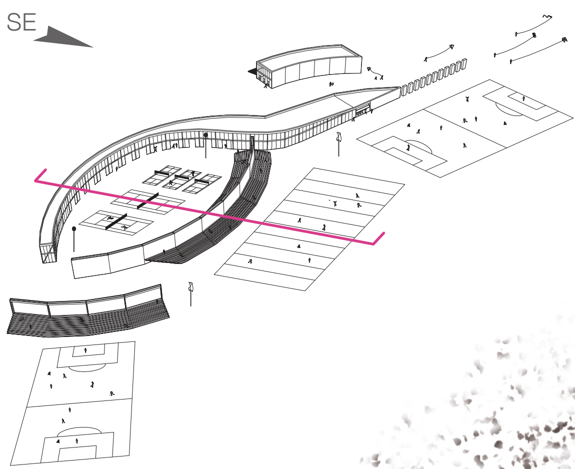


Fig. 6.23. Structural layout for building form and interior program.



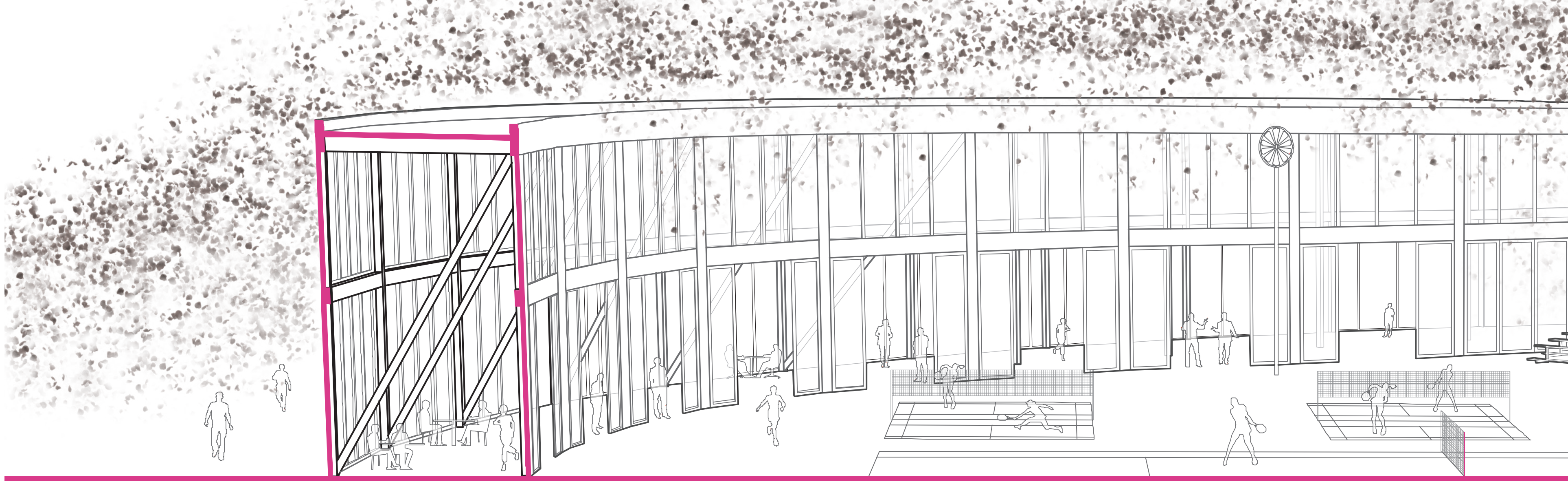
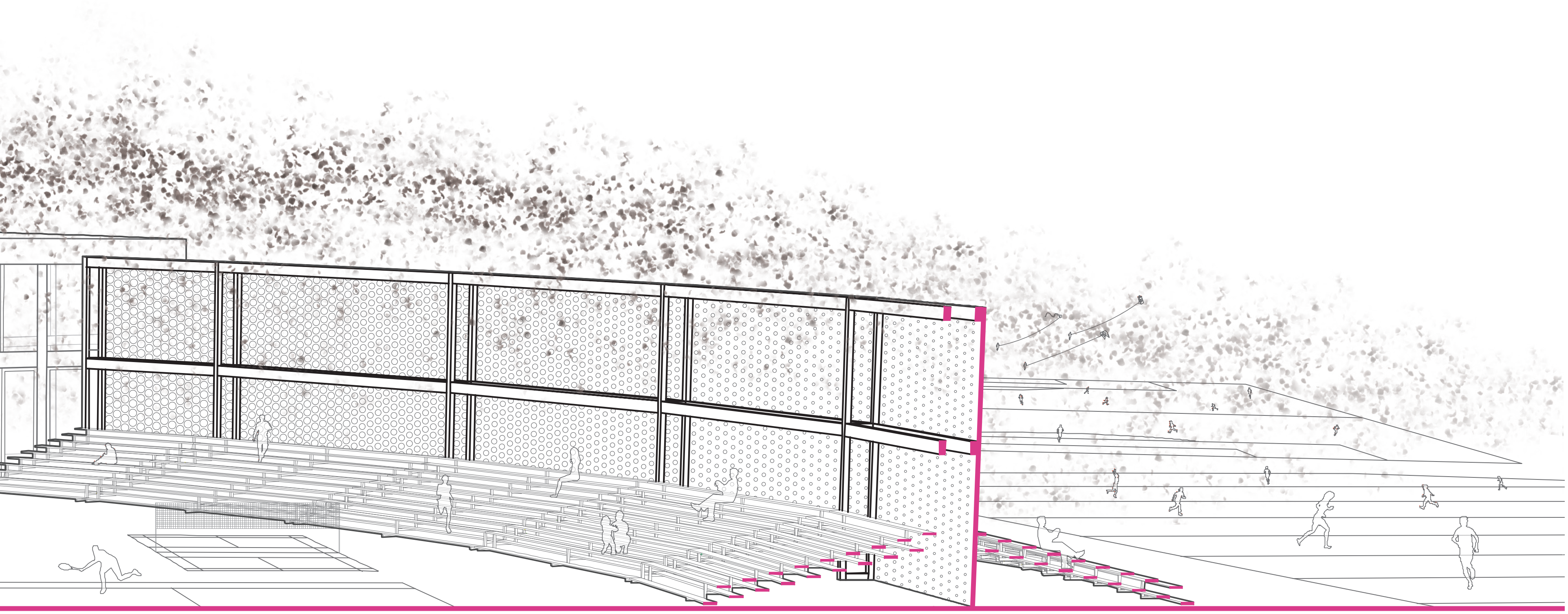


Fig. 6.24. Key drawing (left) and building cross-section (spread).



CONCLUSION

DESIGN METHOD APPLICATIONS

The design method that is developed in this thesis considers the relationship between wind, building form, and building structure, to use the wind in a productive manner instead of simply viewing it as something to be resisted. The use of CFD software allows the architect to form the building to harness the wind for both leisure and economy, through the creation of appropriate wind conditions for the exterior sports programs and the wind energy generation technologies. The combined use of the CFD and FEA software also allows the architect to form the building in a way that reduces the wind loads that are exerted on it, and design the structure to resist the wind loads that cannot be mitigated by the building form.

There are other applications to which this method may be applied in order to harness or manipulate the wind for a specific purpose. The following wind issues should be considered in all building and city design, and they emphasize the importance of considering the relationship between wind and buildings that is the focus of the design method. The method may be applied to building design to address these issues early in the architectural design process.

PEDESTRIAN COMFORT

Although wind tends to slow down in cities, it can interact with buildings in several ways that cause it to speed up or become turbulent at ground level, making it uncomfortable or even dangerous for pedestrians (Fig. 7.1).[1] Tall buildings can direct high-speed wind down their windward faces and to the street level with the downwash effect (Fig. 7.2).[2] Buildings running parallel to each other can channel the wind and accelerate it (Fig. 7.3).[3] Wind also accelerates around building corners (Fig. 7.4)[4] and through small openings in or between buildings (Fig. 7.5).[5]

Building forms may be designed to alter the wind around them

Fig. 7.1. Buildings creating fast or turbulent winds can make it uncomfortable for pedestrians to walk at street level.

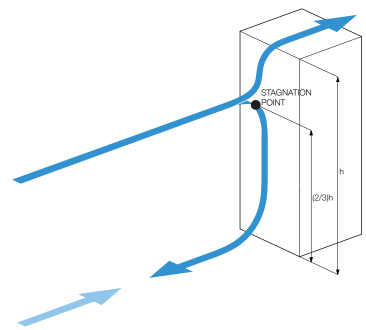


Fig. 7.2. Tall buildings direct high-speed wind down to street level.

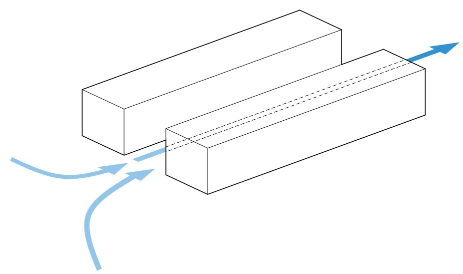
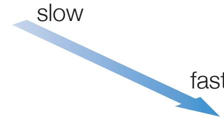


Fig. 7.3. Wind is channeled and accelerated between buildings.



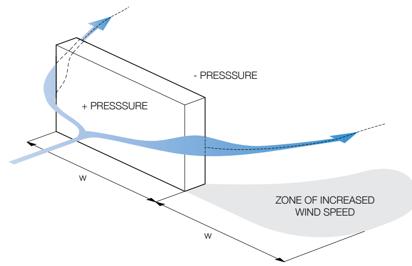


Fig. 7.4. Wind accelerates around corners.

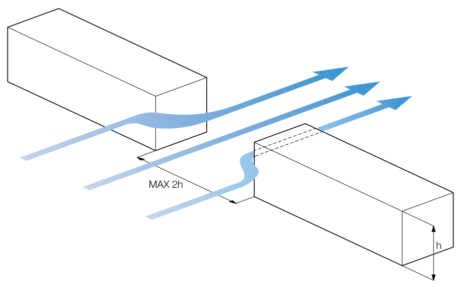


Fig. 7.5. Wind accelerates through openings between buildings.

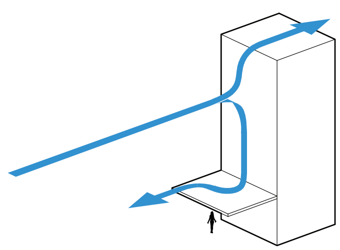
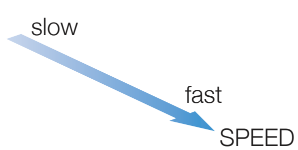


Fig. 7.6. Canopies deflect wind.



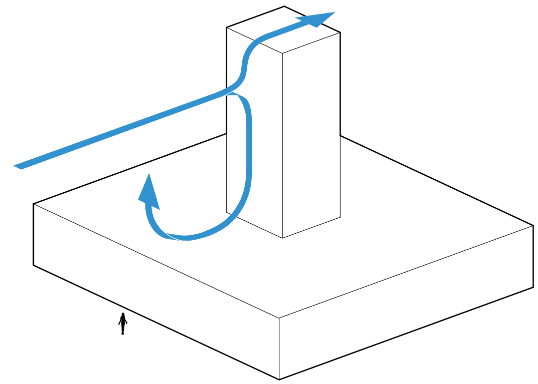


Fig. 7.7. Podiums deflect wind.

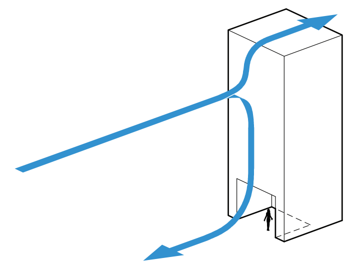


Fig. 7.8. Setbacks shelter pedestrians from downwash.

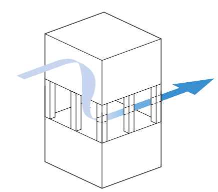


Fig. 7.9. Breezeways deflect wind before it reaches ground level.

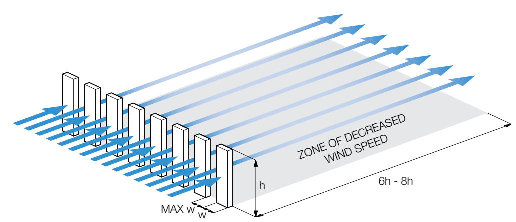


Fig. 7.10. Porous screens decrease wind speed.

so that it is not uncomfortable for pedestrians. For example, canopies (Fig. 7.6) and podiums (Fig. 7.7) reduce the downwash effect by directing the wind away from the ground, while setbacks provide sheltered spaces for pedestrians to walk, out of the flow of the downwash (Fig. 7.8).[6] A breezeway, which is an open space through a building partway up its height, allows the high-speed wind that travels down the windward building face to be deflected horizontally through the opening before it reaches ground level (Fig. 7.9).[7] To reduce wind speed in areas where wind is accelerated horizontally through, around, or between buildings, porous screens may be installed (Fig. 7.10).[8]

The design method that is developed in this thesis may be used to form buildings to create comfortable ground-level wind conditions for pedestrians, rather than wind conditions specifically for sports and energy generation technologies. The same iterative CFD process could be run, but with the goal of reducing wind speed and turbulence at the building's base. After this first step in which the wind conditions around the building are refined, the rest of the steps to develop the building could be carried out the same way as described in the previous chapters.

COOLING AND VENTILATION

For hundreds of years, the wind has been used by architects for natural cooling and ventilation of buildings and cities.[9] If buildings and cities are designed to use the wind advantageously in this manner, they could create more comfortable interior and urban environments while reducing the cooling and ventilation loads on the buildings' mechanical systems. The wind environment therefore should be considered by building designers and urban planners, so that building and city layout, orientation, and shape may be designed to use the winds advantageously.[10]

Building and city form can be designed to alter the wind patterns around and through the buildings, to induce natural cooling and

Fig. 7.11. Small parks in Toronto's downtown.

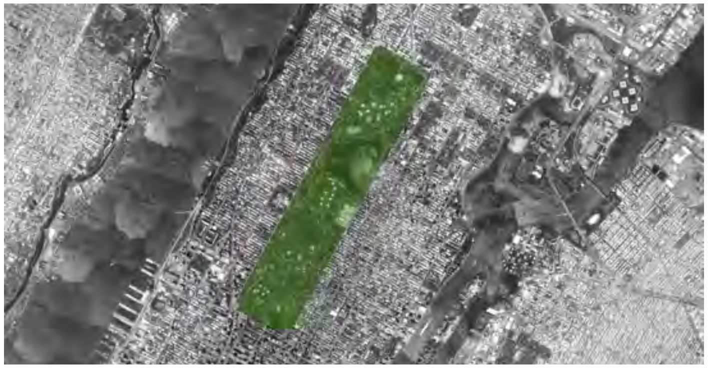


Fig. 7.12. Central Park in New York City.

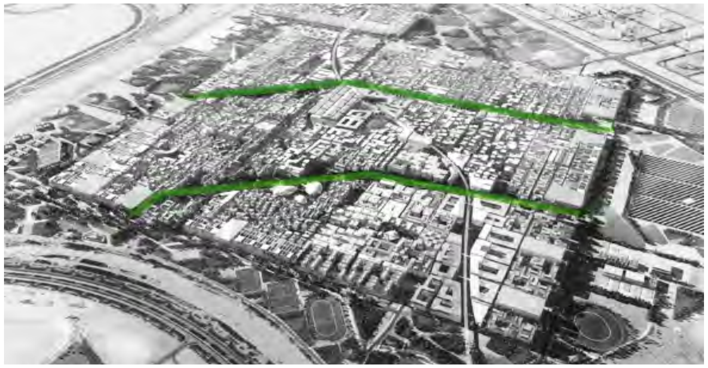


Fig. 7.13. Ventilation corridors in Masdar City.

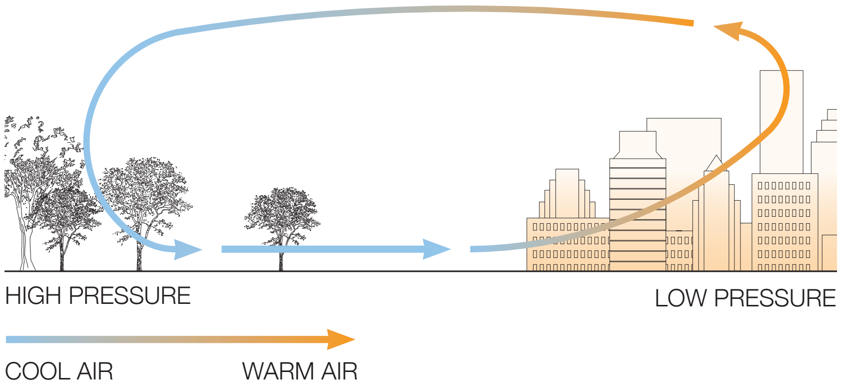


Fig. 7.14. Pressure differentials induce an intake of fresh rural air into cities.

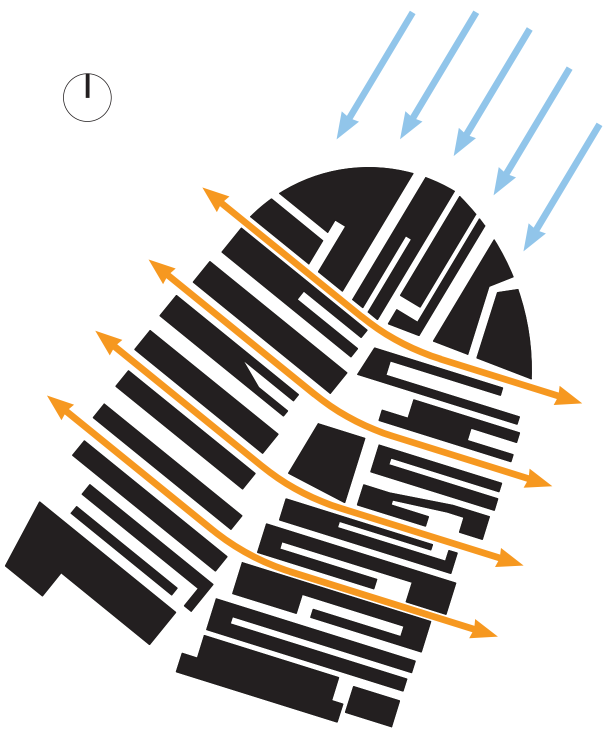


Fig. 7.15. Korčula, Croatia blocks cold winds but is permeable to warm winds.

ventilation. Open spaces are necessary within cities to let the air flow through them to use the wind for cooling and ventilation.[11] This may be accomplished with small open spaces, such as the many small parks across Toronto's downtown (Fig. 7.11), with one large open space, as in the case of New York City's Central Park (Fig. 7.12),[12] or with ventilation corridors running through the city, such as those in the proposed Masdar City in Abu Dhabi, UAE (Fig. 7.13).[13] Cities should also be permeable to the surrounding rural areas so that an intake of fresh rural air is achieved (Fig. 7.14), rather than recycling polluted city air throughout these ventilation spaces.[14] This fresh air moving through the city can then be taken in by buildings for the cooling and ventilation of their interiors. Cities may be oriented according to prevailing wind directions to encourage this flow of air into and throughout the city. For example, the street patterns of Korčula, Croatia, close the city against the cold winter winds from the north, but orient the streets so that the east-west summer winds can enter through these open corridors and ventilate the city when it is needed during the hot months (Fig. 7.15).[15] Similarly, the ventilation corridors of Masdar City are oriented along the axes of the site's two prevailing wind directions, which alternate on a diurnal cycle (Fig. 7.16, Fig. 7.17).[16] During the day, hot winds coming from the northwest flow into the corridors and are cooled as water evaporates into the air from the vegetation (Fig. 7.18).[17] The cooled air then gets diverted down side streets.[18] At night, cool winds from the east enter the city from the other side and are also diverted along side streets (Fig. 7.19).[19]

The design method of this thesis may be applied to the development of buildings and cities that are conducive to natural cooling and ventilation. The CFD simulations may be run for a model of a city or neighbourhood, instead of a single building, to predict the wind flows between the buildings. The city form may be adjusted with the same iterative process as the one described in this thesis to improve the wind patterns for cooling and ventilation of the city. CFD simulations may also be run for a building interior to visualize the air flow within, rather than around, the building. This would allow

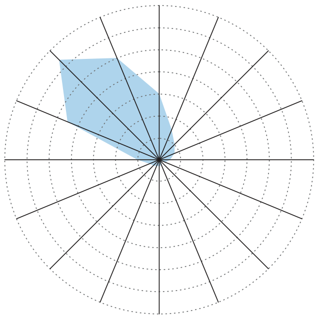


Fig. 7.16. Masdar City day wind rose.

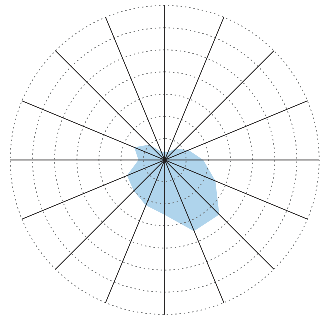


Fig. 7.17. Masdar City night wind rose.

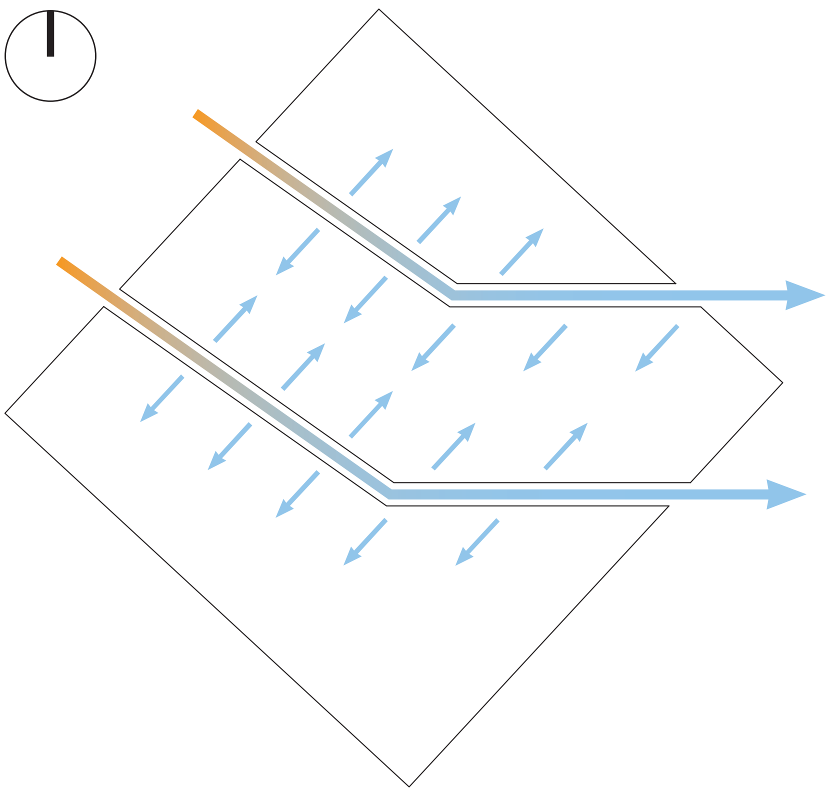


Fig. 7.18. Hot winds from the northwest enter the corridors during the day.

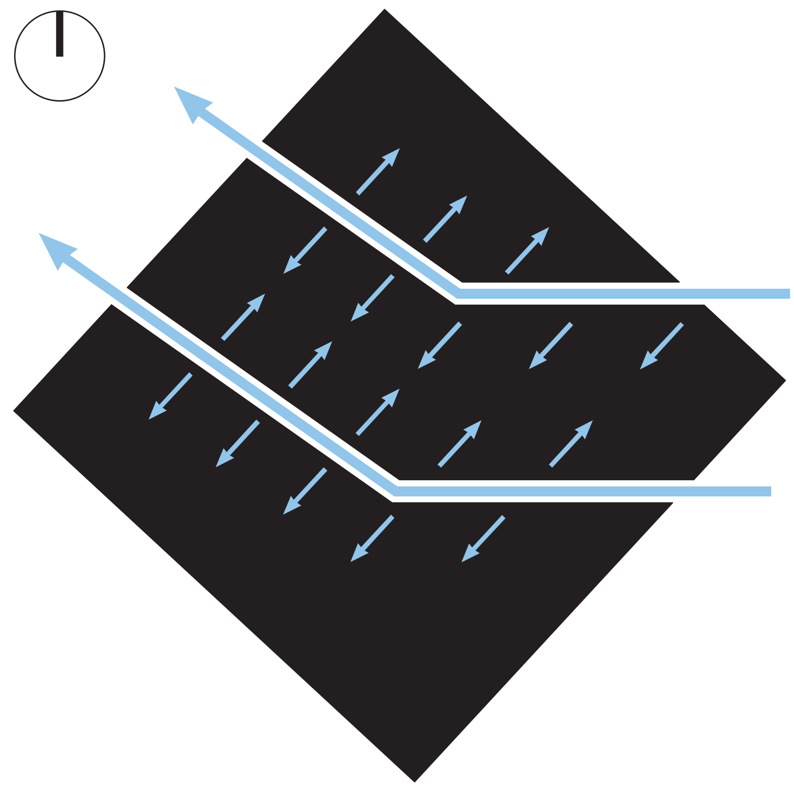


Fig. 7.19. Cool winds from the east enter the corridors at night.

the architect to make adjustments to the interior layout to improve the natural cooling and ventilation within the building.

POLLUTANT DISPERSION

Fig. 7.20. Winds disperse pollutants in urban areas.

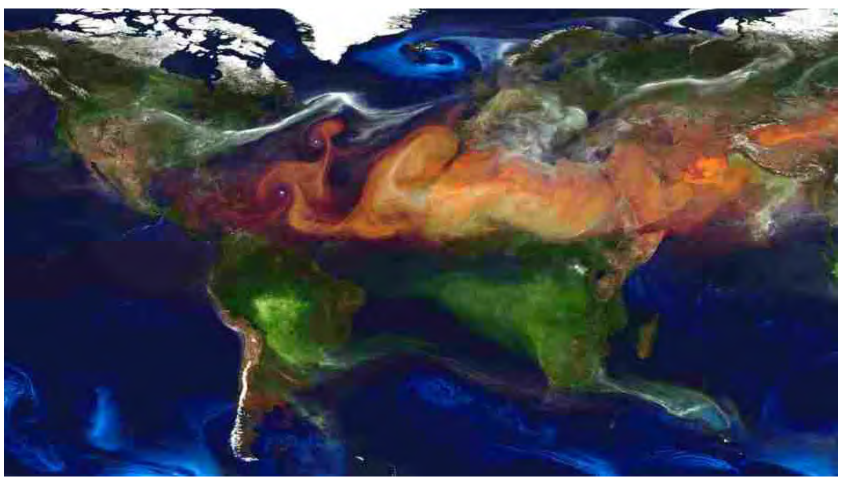


Fig. 7.21. Global winds carry air pollution around the world.

All winds, from strong to weak, disperse pollutants in urban areas (Fig. 7.20).[20] This is because cities emit their own pollutants,[21] but also because global winds carry pollutants around the world (Fig. 7.21) to contaminate cities that may not produce as much pollution themselves.[22] Winds can either spread these pollutants throughout the city, or carry them away from the city.[23] Pollutant dispersion should therefore be a consideration in architectural and urban design, so that buildings and cities may be designed to remove pollutants from the air and make the environment healthier for its residents.[24]

Building forms can alter the wind patterns around them, so that pollutants are carried by the wind away from or out of the city. For example, the open spaces that may be used for city ventilation should distribute clean air, rather than contaminated air, throughout the city. These ventilation spaces should therefore not be near industrial zones, major highways, or other areas that produce a lot of pollution.[25] It is especially advantageous if these ventilation spaces are planted with vegetation, as the temperature difference between the warmer city and the cooler green space induces wind flow from the green space into the city, in the same way wind flows into the city from surrounding rural areas.[26] The clean air from the green space moves into the city to cool, ventilate, and remove pollutants rather than distribute them.[27] Cities may also be designed to direct winds from one direction through the city for cooling and ventilation, while directing winds from another direction overtop of the city so that they do not mix with the air at ground level.[28] If winds from a certain direction tend to carry pollutants, either from international sources carried by global wind patterns, or from local pollution sources, this strategy can direct the polluted winds up and over the city. Such a strategy is employed in the design of

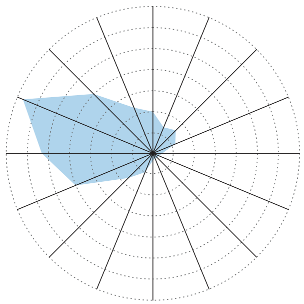


Fig. 7.22. Xeritown day wind rose.

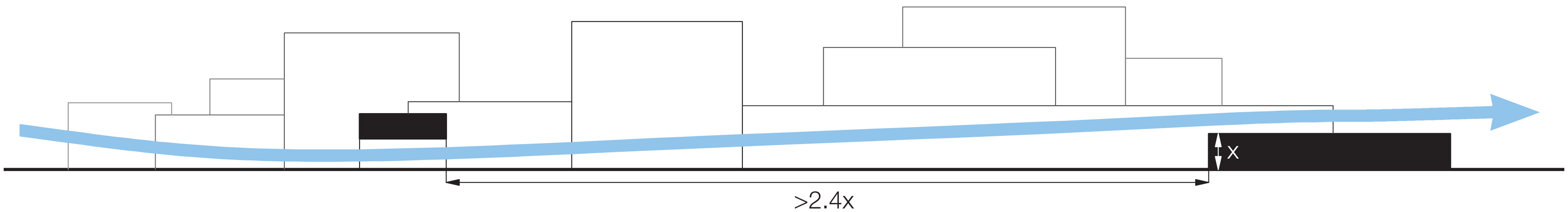


Fig. 7.23. During the day, cool winds are channeled through the city for cooling and ventilation.

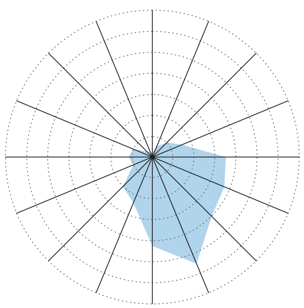


Fig. 7.24. Xeritown night wind rose.

Fig. 7.25. At night, hot winds are diverted over the tops of the buildings.

Fig. 7.26. Xeritown.

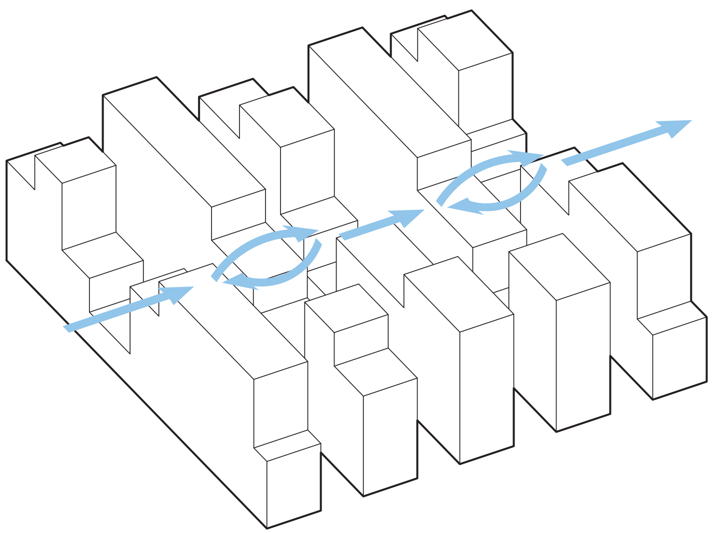


Fig. 7.27. Varied building heights induce turbulence at the skyline.

Xeritown (Fig. 7.26), a proposed extension of Dubai, UAE, although it is used to force hot, rather than polluted, winds over the city.[29] During the day, the cool winds from the sea (Fig. 7.22) are channeled through the city for cooling and ventilation (Fig. 7.23).[30] Long, open spaces are aligned in the direction of these winds so that the wind will dip down into them and cool the ground level.[31] This may be achieved with open spaces that have a width-to-height ratio of at least 2.4.[32] At night, the hot wind that comes from the desert (Fig. 7.24) is diverted over the tops of the buildings (Fig. 7.25).[33] In this direction, the buildings are stepped up towards the centre of the urban area, with the rising edges facing the oncoming desert winds.[34] The spaces between the buildings in this direction have a width-to-height ratio of less than 0.7, so that the wind will skim overtop of the openings instead of moving down into them.[35] These two strategies ensure that the unwanted hot winds blow up and over the city instead of heating up the street level. These strategies could also be employed to ensure that polluted winds from one direction are kept out of the city, while the city is kept permeable to clean air from another direction. Another strategy is to vary building heights along a city skyline to induce turbulence at the tops of the buildings (Fig. 7.27).[36] This turbulence exchanges polluted air closer to ground level with fresher air from the top of the city, to continually recycle the air at street level.[37] The skyline of Xeritown was designed to have building heights with enough variation to induce this air cycling and remove pollutants.[38]

The design method developed in this thesis may be used to create urban forms that direct pollutants out of, rather than throughout, the city. With CFD simulations of wind patterns, the user may visualize where pollutants will be distributed by these winds. This allows them to develop iterations of the urban area, so that its form creates wind patterns that will minimize pollutant dispersion within the city.

SNOW AND ICE ACCUMULATION

When wind blows snow and ice, it affects where snow and ice accumulates on and around buildings. This can cause particular issues that are addressed in building codes. The Ontario Building Code, for example, stipulates that buildings must be designed so that exit doors are never blocked by the accumulation of snow or ice for consistently accessible egress (Fig. 7.28),[39] and that snow and ice may not accumulate over vents for air intake or exhaust so that the building's ventilation is not compromised (Fig. 7.29).[40] Without paying particular attention to a site's wind patterns during building design, the ways in which snow and ice accumulation will happen can be difficult to predict, and can cause these problems to occur after construction is complete. The Ontario Building Code also specifies that the building structure and cladding must be designed to withstand snow loads (Fig. 7.30),[41] and provides formulas that may be used to calculate the design snow load for a particular building on a particular site.[42] However, these formulas only provide snow load values for a small number of building forms and environmental situations.[43] For example, the role that the wind plays in the accumulation of snow, and the resultant snow load that is exerted on the building, is only considered with the wind exposure factor in the provided formula.[44] This factor is determined based on only the number of sides of the building that are exposed to the wind, and the nature of the building's roof obstructions that would block the wind flow.[45] The more the building is exposed to the wind, the more the wind exposure factor may be reduced, which reduces the snow load that the building must be designed to resist.[46] Similarly, the building form is considered in the formula with only the slope factor, which is determined by the slope of the roof and the roofing material,[47] and the shape factor, which depends on the shape of the roof, the presence of roof valleys in which snow could accumulate, and the number of roof levels between which snow could drift.[48] These factors can sometimes be too generic to allow the designer to ensure that wind-induced snow and ice accumulation will not overload the building,[49] so it is beneficial to study in more detail the ways in which wind affects snow and ice accumulation on a particular building and site.

Buildings may be formed so that snow and ice is not accumulated

Fig. 7.28. Snow can block doors.

Fig. 7.29. Snow can block vents.

Fig. 7.30. Buildings must be able to withstand the load exerted by snow.

Fig. 7.31. Simulated snow on a building model in a wind tunnel.


Fig. 7.32. Svalbard Science Centre.


Fig. 7.33. Physical model.

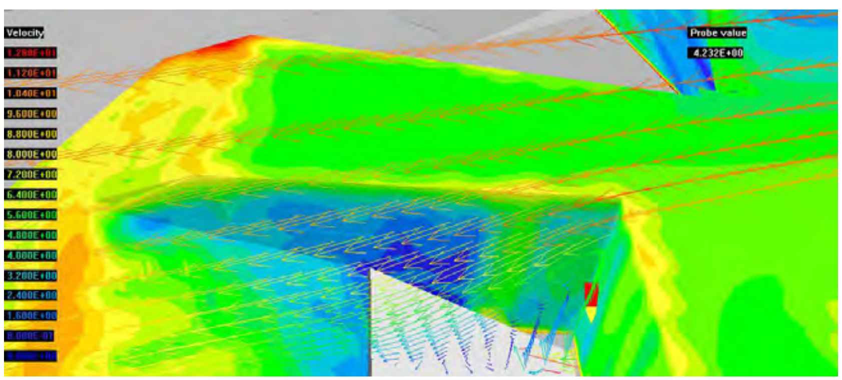


Fig. 7.34. CFD simulation.

in undesirable areas. The accumulation patterns may be tested with a building model in a wind tunnel, using simulated snow made out of, for example, crushed walnut shells, sawdust, or sand (Fig. 7.31).[50] This allows the designer to visualize how snow will fall and accumulate on a building while the wind is blowing, or how the wind will cause snow that is already on the ground to drift and build up on and around the building.[51] The results of the wind tunnel test may also help to determine the design snow loads that should be used when designing the building's structure,[52] rather than relying on the more generic formulas provided by the building code. CFD software may also be used to simulate how the wind will impact snow and ice accumulation. The Svalbard Science Centre (Fig. 7.32) by Jarmund/Vigsnaes AS Architects was designed using CFD software for this purpose.[53] Consideration of the strong wind flows across the site was a primary driver in the generation of the building's geometry, as its irregular plan, pitched roofs and sloped walls were formed to avoid unwanted snow drifts around doors and windows.[54] This is an especially important consideration because of the building's northern location in Longyearbyen, Norway.[55] Through several iterations, the building form was tested with both physical models (Fig. 7.33) as well as more detailed CFD simulations (Fig. 7.34) to visualize where the wind would blow the snow around the building.[56] Both of these kinds of tests allow the architect to design the building form to control the accumulation of snow and ice. This avoids the accessibility and loading issues that are associated with unwanted accumulation.

The design method of this thesis may be applied in a similar manner. The user may run the CFD simulations particularly to observe the ways in which the site's wind patterns would cause snow and ice to accumulate on and around the building. Through the iterative process, the building form could be refined so that snow and ice accumulates only in desired areas, to keep entrances and exits accessible, to keep windows clear to let natural light into the building, and to reduce the snow loads acting on the building.

SUMMARY

A design method (Fig. 7.35) in which architects use wind effects and loading as a design generator may be carried out with a pairing of computational fluid dynamics software and finite element analysis software.

STEP 1 | FORM AFFECTS WIND

First, a building form is modeled in Vasari, and a CFD simulation is run in Vasari to visualize the wind speeds and patterns that are created around the building by the building form. The architect then makes observations and adjusts the form within Vasari for the next iteration to improve the appropriateness of the surrounding wind conditions for the exterior programs. They may repeat this step to refine and re-test many iterations of their design until the building form creates the desired wind conditions.

STEP 2 | WIND AFFECTS FORM

In the second step, which is carried out concurrently with the first step, a CFD simulation is run in Flow Design to evaluate the aerodynamics of the building form by providing information about the wind pressure that is exerted on each building face. The architect then makes observations and adjusts the form for the next iteration to improve the form's aerodynamics. This step may be repeated until the building form has the desired aerodynamic properties.

STEP 3 | WIND AFFECTS STRUCTURE

Next, the wind pressure information that is provided by Flow Design is used to divide the building form into pressure zones based on the areas that are subjected to approximately the same amount of wind pressure. A structural bay is then modeled for one of the pressure zones and tested with Scan&Solve by inputting gravity loading and the average positive and negative wind pressure values for that zone that were obtained from Flow Design. If there is too much deflection, the architect adjusts the model of the bay to increase its stiffness and reduce its deflection under wind loading, and then tests the adjusted model with Scan&Solve until the bay is able to resist large movements in the wind. This step is repeated to develop a bay for each pressure zone and the bays are laid out within the building form to create the building's structural system.

STEP 4 | PROGRAM AFFECTS FORM AND STRUCTURE

Finally, the form of the building is adjusted so that it could feasibly accommodate both exterior and interior programs. This adjusted model should be tested with a CFD simulation in Vasari to ensure that the changes to the form did not negatively alter the wind conditions around the building. The layout of the structural bays is then adjusted to fit within the refined form. This step completes the feedback loop between the CFD and FEA software, and the design method may be repeated as many times as necessary to develop a building that both shapes and resists the wind.

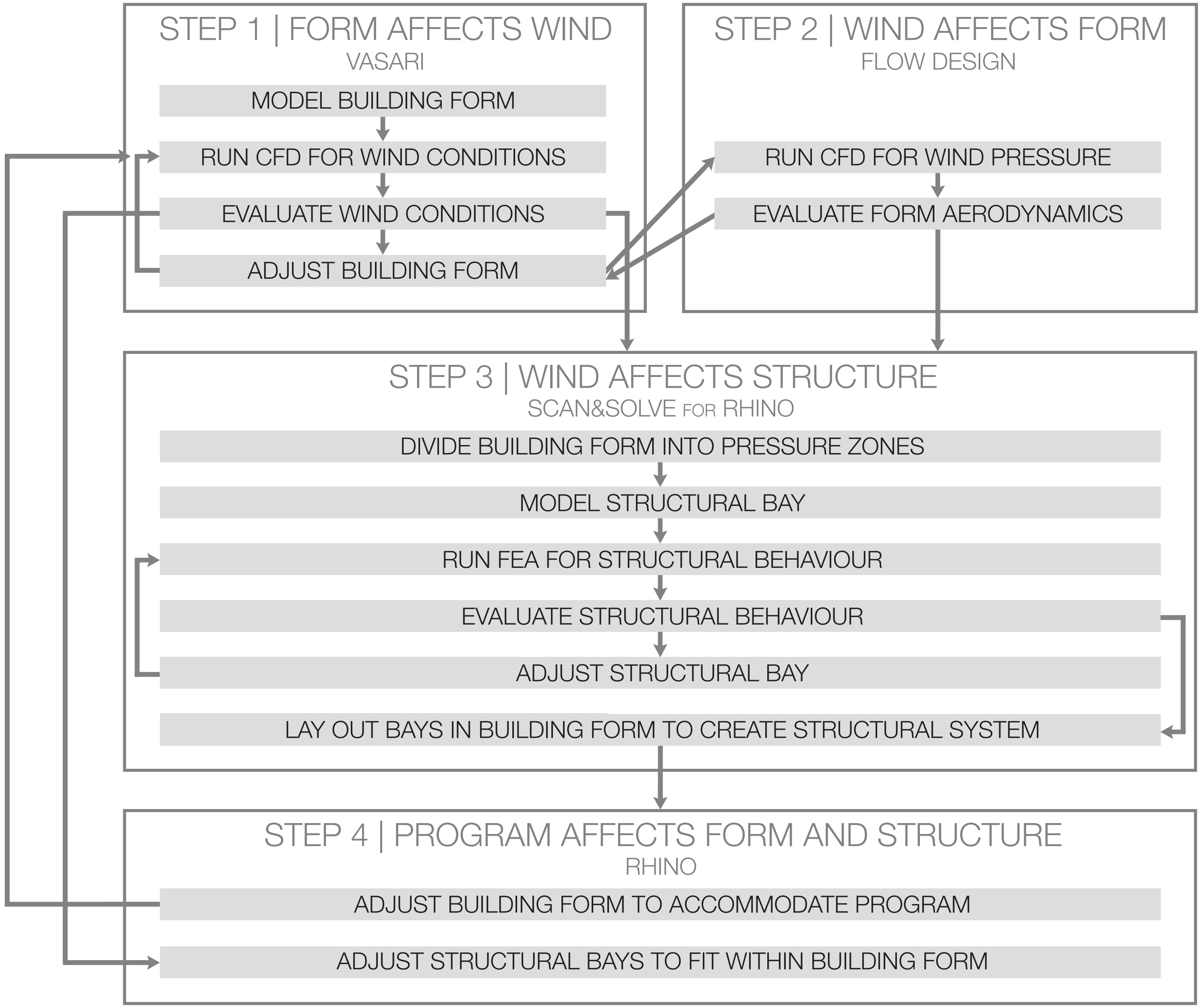


Fig. 7.35. Design method sequence.

Constant feedback is an important part of a designer's workflow. It allows the designer to test a design iteration, receive feedback about how their design works, evaluate how well it works for its required purposes, and then learn from this feedback and apply it to subsequent design iterations. Throughout this process, they begin to understand which aspects of their designs work for their purposes and which do not. Feedback is especially important in an architectural workflow when the architect is working with disciplines in which they are not extensively trained, such as wind and structural engineering. Feedback is essential for them to learn how their designs interact with the wind, since it is unlikely that the architect would already possess an intuitive understanding of this relationship. The design methodology that is developed in this thesis provides this essential feedback through the CFD and FEA software, as it produces visual output to show the architect how their design influences wind speeds and patterns, moderates wind pressure, and reacts to wind loading. Software has a lot of potential to allow architects to work within the realms of wind and structural engineering, as it means that they do not need to have extensive engineering knowledge to be able to test many design iterations in relation to these considerations. Through the feedback provided by these tests, they can learn what the analysis results mean and how changes to their design affects these results. This feedback informs their subsequent design iterations, and eventually the architect will develop an intuition of how to form their buildings to control how they interact with the wind. This is beneficial for practicing architects who work with disciplines that are tangential to architectural design, as well as architecture students who may learn through this feedback while they are in school, and then apply this learned intuition in the workplace after graduation.

The feedback loop that is developed in this thesis may easily be incorporated into existing architectural working practices, to enhance them rather than change them. The method uses software that is easy for architects to learn without previous experience with similar software, and the software automates complex processes to make it easier to use. All of the programs are also compatible with each other, expediting the process of exporting and importing model files between programs. The selected software is compatible with 3D-modeling programs that are already commonly used in architectural offices, and may be run on typical computer hardware that is already owned by most firms. The feedback that is provided by the software is also in the form of visual output, conveying wind patterns and forces through a medium that architects are trained to understand. All of these considerations make the design method feasible to integrate into current architectural practices, both within their current hardware and software use, as well as their interpretation and production of graphic output.

The design method is also easy to integrate into architectural workflows because designers may implement only one step of the method at a time to develop specific aspects of their designs. The fact that each of the steps within the method may be repeated as many times as necessary means that they may also stand alone as iterative, repeatable processes in themselves. For example, step one may be used to run CFD simulations to evaluate and adjust building form iterations for considerations of pedestrian comfort, cooling and ventilation, pollutant dispersion, or snow and ice accumulation, as described in the previous section of this chapter. The second step could be carried out on its own for detailed aerodynamic studies of building forms. Even if wind was not a major consideration in a building design, the third step of the method could be integrated into the architectural design process to develop a schematic structural system for the project, inputting into the FEA software the loads that are applicable. The ease with which the steps may be separated makes them feasible to integrate into current architectural practices, because only the steps that are relevant to a design stage need be carried out. The method may therefore be used to consider wind, structure, or both in the architectural design process, depending on the designer's specific needs.

Using CFD and FEA software in a way that is appropriate for architectural applications allows architects to integrate wind and structural engineering considerations into the early design stages of their current working practices. As CFD and FEA programs continue to be improved, the accuracy and usefulness of this method will increase. It is the hope of the author that software programmers may draw from this method to create more accurate CFD and FEA programs that are conducive to architectural applications, so that in the near future, architects may use this design methodology to integrate wind, structural and architectural design processes.

DISCUSSION AND FURTHER DEVELOPMENT

The defence of this thesis generated discussion about the further development of this design methodology. Considerations of more complex wind conditions, as well as the aesthetic design of the building, should be incorporated into the method if it is to be developed in the future.

The design methodology was carried out in this thesis within a simple wind condition of two predominant wind directions that are opposite to each other. This provided simple parameters within which to develop and test the method. However, it was brought up in the discussion that many sites have different, more complex wind conditions, and the question was raised as to whether or not the design method would be able to be carried out within these other conditions. As such, the first step in the further development of the design method would be to test the method within different wind conditions. Repeating the method with different parameters would inevitably reveal steps of the method that were designed to work best within the original site conditions, and may not work as well within the new conditions. Working through these issues as they are discovered, and developing the method within multiple wind conditions, would allow the method to be refined until it could be applied within the conditions of any given site or project.

The process by which the design method is carried out would be slightly different, for example, on a site with more than two predominant wind directions. In the first step, CFD simulations would have to be run for each of the wind directions. This would take more time, and would require the building to be designed so that appropriate wind conditions for the exterior programs were created within all of these conditions, which could be more challenging to accommodate. However, the process of the first step would essentially be carried out the same way. The second step would also become more challenging, as the building would ideally need to be formed in a way that optimizes its aerodynamics within many wind directions, instead of just two directions along the same axis, as considered in this thesis. Finally, the third step could be carried out much in the same way as in this thesis, but the architect would have to find the worst-case loading condition for each pressure zone out of all of the predominant wind directions, instead of just looking at two. All of these considerations would make the design method take longer to execute, although testing the method within multiple site conditions could potentially reveal ways of streamlining the method. Also, these tests would inevitably reveal more complications that are not predicted here. However, repeating this method within several different wind conditions would be a necessary step in the development of the design methodology, to ensure that it may be used for any site or project.

It was also brought up in the discussion following the defence that because the building was formed almost entirely based on considerations of surrounding wind conditions and form aerodynamics, the aesthetic and functional considerations that normally drive the architectural design process do not influence the resulting building form. The method could therefore be developed to provide a step in which these factors would influence the design, so that the building could be created based on considerations of both engineering and architecture. This could be accommodated by expanding the fourth step to allow the building form to be adjusted more substantially based on programmatic considerations or building aesthetic. The resulting building would, however, need to be re-tested with the design method to see how the new form and structure functioned within the site's wind conditions. The building may then need to be adjusted to fix any wind-related issues that may result. A potentially more streamlined approach would be to create a schematic building design first, based only on architectural considerations, and then run the design methodology to adjust the form to create more desirable surrounding wind conditions and to improve its aerodynamics. The building structure could then be designed with the methodology to fit within this form that is the product of both architectural and engineering considerations.

Even if this design methodology is not developed further after this thesis, it has still provided me with insights that I may apply in the architectural field. It has allowed me to gain an understanding of engineering topics that are often tangential to architectural design. Having an understanding of these considerations, even if not a mastery of them, will help with the collaboration between architects and engineers that is a necessity in architectural practice. This would provide the opportunity to work with architects to make them aware of the implications that wind and structural engineering considerations may have on the architecture of a building. It would also allow for the possibility of involvement in wind or structural engineering design processes, as the knowledge gained in this thesis would allow me to collaborate more efficiently with engineers, while offering an architect's perspective on these wind and structural considerations.

Whether the design methodology itself is developed further, or whether the insights gained from it are applied to architectural practice, it has been a valuable investigation into the integration of architectural and engineering design.

ENDNOTES

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Ziad Boutanios, PEng., BinkZ, e-mail message, July 3, 2015.

GLOSSARY

AERODYNAMIC	the quality of a form to have a shape that reduces drag caused by surrounding wind
AERODYNAMICS	the study of the interaction between solid forms and air when at least one of them is in motion, not necessarily referring to solid forms that are shaped to reduce drag caused by surrounding wind
ALONGWIND LOAD	wind load acting in the direction parallel to the mean wind velocity
ASPECT RATIO	ratio of height to width
COMPUTATIONAL FLUID DYNAMICS (CFD) SOFTWARE	software that simulates the flow of fluids, including wind, around an input model and produces numbers, graphics and animations to convey this flow
CROSSWIND LOAD	wind load acting in the direction perpendicular to the mean wind velocity
DEFORMATION	the action of a body changing shape as the points within the body displace different amounts
DISPLACEMENT	a measure of where and by how much a point of a body moves while the body experiences stress
DYNAMIC WIND LOAD	wind load that rapidly changes in magnitude or location
FINITE ELEMENT ANALYSIS (FEA) SOFTWARE	software that evaluates the structural behaviour of an input model under input loading conditions and produces numbers, graphics and animations to convey this behaviour
FINITE ELEMENTS	small pieces into which a digital model is divided to be analyzed by FEA software
FUNDAMENTAL PERIOD	the length of time required to complete one oscillation
LEEWARD	(adj.) the side of an obstruction that is sheltered from the wind (adv.) on the side of an obstruction that is sheltered from the wind

MESH	A set of finite elements made up of points, edges, and faces that approximate the original model
MESHING	the process of representing a physical entity with finite elements, by breaking it down into smaller pieces to re-build it as a set of points, edges, and faces that approximate the original model
QUALITATIVE STRUCTURAL UNDERSTANDING	the ability to know how a structure behaves without referring to measurements or calculations
QUASI-STATIC WIND LOAD	static wind load with an increased magnitude to account for the wind load's dynamic nature
STATIC WIND LOAD	wind load that maintains a consistent magnitude and location over a period of time
STRAIN	a quantity that describes deformation in a direction
STRESS	a quantity that describes all the internal forces acting within a body of material
STRUCTURAL ANALYSIS	the process of calculating the types and magnitudes of stresses and deformations in a structure subjected to loads
STRUCTURAL BEHAVIOUR	the manner in which a structure acts or functions under loading conditions
STRUCTURAL DESIGN	the process of determining the form of a structure that will allow it to withstand subjected loads
STRUCTURAL INTUITION	the ability to immediately understand how an object or material will act under load, without necessarily knowing why
TORSIONAL LOAD	wind load that induces twisting about the vertical axis
UPLIFT	wind force acting upwards in the direction perpendicular to the mean wind velocity
WINDWARD	(adj.) the side of an obstruction that is facing the wind (adv.) on the side of an obstruction that is facing the wind

APPENDIX A | PAPER FOR ICWE14

This appendix is a paper that was co-wirtten by the author of this thesis for publication and presentation at the 14th International Conference on Wind Engineering, which took place from June 21-26, 2015 in Porto Alegre, Brazil. The paper is a summary of the content of this thesis.

ICWE14 June 21-26, 2015 | Porto Alegre - Brazil 14th INTERNATIONAL CONFERENCE ON WIND ENGINEERING

CFD and FEA Software in Architectural Design Methods

Stephanie Fleming[1], Elizabeth English[2]
[1] School of Architecture, Faculty of Engineering, University of Waterloo, Waterloo, Ontario, Canada
[2] School of Architecture, Faculty of Engineering, University of Waterloo, Waterloo, Ontario, Canada
email: skflemin@uwaterloo.ca, english@ecenglish.ca

ABSTRACT: There is a reciprocal relationship between wind and buildings, as they each affect the other. Building form affects wind by altering its speed and flow patterns, and can be used to create desirable wind conditions for a set of exterior programs. Wind, in turn, exerts load on the building, which can be reduced with aerodynamic forms and resisted with appropriate structural systems. This establishes a relationship between wind conditions, the building form that influences these wind conditions, and the structure that stabilizes the form against these wind conditions. This relationship is investigated through the development of a design method that allows architects to consider, in the early architectural design stages, how wind and buildings affect each other. The method consists of a pairing of computational fluid dynamics (CFD) software and finite element analysis (FEA) software. For each building design iteration, CFD software is used to simulate the speeds and patterns of wind flow around the initial building form design, as well as evaluate the aerodynamics of the building form by providing information about the wind pressure that is exerted on each building face. The speed with which these results are provided allows the architect to refine and re-test many iterations of their design until the building form creates the desired wind conditions. Then, the wind pressure information that is provided by the CFD software is input into the FEA software to predict how the building will react to combined wind and gravity loading. This information informs the schematic design of the building's structural system, which is developed through another iterative process using the FEA software. This method allows architects to consider wind as a generator of architectural form within a streamlined, software-based workflow.

KEY WORDS: Computational Fluid Dynamics; CFD; Finite Element Analysis; FEA; Architectural Design; Design Method; Form Generation; Aerodynamics; Structure.

1 INTRODUCTION

In antiquity, the architect was the "master builder" who understood and was able to execute both building design and construction. However, when the Industrial Revolution spurred the rapid creation of many new building materials and technologies, it became difficult for a single person to master them all. This fostered the creation of the structural engineering profession. Structural engineers became experts in building construction technologies, while architects specialized in the spatial and aesthetic design of buildings. This has resulted in a divergence between the roles and priorities of the architect and the structural engineer. [1] This divergence is commonly seen within current architectural practice, as structural analysis is not often integrated into early architectural design phases. Instead, it is performed by an engineer after the initial building design has already been developed by the architect, at a point when it is difficult, costly, and time-consuming to change the design to accommodate the structure. This divergence between structural and architectural processes is widely acknowledged in the fields of both architecture and engineering, and members of both professions have worked on developing methods of integrating the two design processes. This paper explores one such method of integration, through the creation of a design method that architects can use to consider wind loading and effects as design informants that are integrated into the initial architectural design phases.

The design method that is described in this paper integrates both structural and wind engineering considerations into early architectural design stages by pairing CFD software and FEA software. Software can be a valuable design tool for architects because it allows them to integrate engineering considerations into their current architectural practices, without having to acquire extensive engineering knowledge. It provides visualizations of wind patterns and structural behaviour, which are easier than numerical data for architects to understand and interpret, since they are trained in visual media. Software also provides architects with a means of quickly testing multiple design iterations in relation to these engineering considerations, because the software can perform engineering calculations and simulations much faster than if the architect were to learn and perform these calculations themselves. Repeated use of the software allows the user to gradually develop an intuitive understanding that allows them to predict what the results of the software analysis will likely be, which will eventually influence their design decisions even before the software analysis is run [2].

Due to current software limitations, this design method may not necessarily produce accurate wind and structural data. Instead, this method will increase in accuracy as CFD and FEA programs continue to be improved. In the future, CFD and FEA software programmers could potentially draw from this method to create programs that can be used together, to allow architects to consider wind during the early design stages within a streamlined workflow. This design method does not intend for the architect to replace the structural or wind engineer. Instead, it equips the architect with the necessary knowledge and tools to design a building that considers wind effects and building aerodynamics in its initial form generation, which may be refined by the wind engineer in a later design phase. The method also allows the architect to design a building that accommodates a feasible structural system that the structural engineer can then easily adjust and detail. This approach allows the architect and engineers to work towards shared goals, thereby streamlining co-ordination between them. It also eliminates costly and time-consuming design revisions that can occur when wind effects and loading are only considered in the later stages of the design process.

2 SOFTWARE

2.1 CFD and FEA Software in Architectural Applications

In this design method, computational fluid dynamics (CFD) software is used to simulate and represent the flow of wind around buildings, and provide information about the amount of wind pressure that acts on the building faces. Visual, rather than numerical, output is used, as it is easier for architects who are not trained in wind engineering to understand and interpret results that visually represent the wind, rather than quantify it.

Finite element analysis (FEA) software is used to simulate how a digital model will react to applied forces. When loads, restraints, and material properties are applied within the software to the digital model, the software breaks down the digital model into small pieces called "finite elements" and analyzes the behaviour of each of these elements under the input loading, restraints, and material properties. Splitting the model into small, simply-shaped elements allows them to be analyzed with simple equations, rather than using complex equations on the entire digital model. The assembly of the behaviour of all of the finite elements conveys the global structural behaviour of the entire digital model. In this design method, FEA software is used to simulate and represent the effects of combined wind and gravity loading on the building's form and structural system. Graphics and animations of structural behaviour are used instead of numerical data, as they are more easily understood by architects who are not trained in structural engineering. [2, 3]

Most CFD and FEA software programs are intended for use in engineering, rather than architectural, applications. This design method selects software programs that can be adapted for use in architectural applications, and uses them in a way that is appropriate for the initial architectural design stages.

2.2 Software Selection

To ensure that this design method is accessible to architects, many types of CFD and FEA software programs were researched to determine which are most appropriate for architectural applications. In order for a CFD or FEA software to be considered for use in this method, it has to meet the following required criteria:

1. 3D-modeling software compatibility: The software must either be a plug-in for, or run files from, 3D-modeling programs that are commonly used by architects or geared towards architectural, rather than engineering, applications. Rhinoceros and Revit are two such programs, so the chosen CFD and FEA programs must be compatible with at least one of these two programs. Rhinoceros can be used to create initial building massing models on which wind studies may be performed. The building can then be modeled in Revit to continue to develop the project and its wind studies in more detail through the later project phases. Executing the design method with these two programs eliminates the need for architects to learn new 3D-modeling software in addition to the CFD and FEA software, making the design method more accessible to architects.
2. Open-source software: The software must be free for students, to encourage its use in a studio setting. This would allow students to learn these programs while in school, so that they would be proficient in them when seeking jobs after graduation. This criteria would make it more feasible for architectural firms to adopt these software programs into their current working methods, since it would be easier to find employees who know how to use them. It is advantageous if the program is also free for commercial use; however, since architectural firms have greater financial resources than students, and since very few programs are free for commercial use, it is not a requirement.

After the elimination of software that did not meet the above criteria, the remaining programs were evaluated based on the following factors:

1. Ease: It is advantageous if the software is easy to learn, as architects will be more inclined to learn it. This also allows them to implement the design method sooner, instead of spending more time learning a complex software.
2. Speed: It is advantageous if the software is able to quickly provide the user with results. This includes considerations of how fast a model can be set up for evaluation, any geometry clean-up that the software might require, and how long it takes the software to process a result. The faster the program can work, the more design iterations can be tested and refined.
3. Accuracy: It is advantageous if the software provides accurate analysis results. However, this factor is the least valued, as for the purposes of initial design development, it is more advantageous to use a program that is easy to learn and that quickly tests multiple design iterations, rather than use one that is complex but provides completely accurate data. For

example, it is better for this method to employ a CFD program that is fast but less accurate, since no CFD software is as accurate as a physical wind tunnel. The chosen CFD programs therefore simulate general patterns of wind flow, but are not relied upon for quantitative results. It is also preferable to select an FEA software that is easy to use, rather than one that provides accurate results but is too complex to be feasibly integrated into the initial design stages. The purpose of this paper is to develop a methodology that will become more accurate as CFD and FEA software is improved, so accuracy is not as important at this stage of the method's development.

4. 3D-modeling function: It is advantageous if the software includes 3D-modeling functions, because once the CFD or FEA results are obtained, the design can be adjusted accordingly within the same program. This eliminates the need to switch programs to make the changes to the digital model, and then re-export the model to run the evaluation. This speeds up the design method.
5. Price: It is advantageous if the software is inexpensive, as it is more feasible that architectural firms would implement a design method that uses inexpensive software into their working practices.

Based on the evaluation of these five factors in relation to the considered software programs, Autodesk Vasari and Autodesk Flow Design are the selected CFD programs to be used in the design method, and Scan&Solve is the selected FEA program.

2.3 Autodesk Vasari

Autodesk Vasari was designed to be used for initial massing, environment, and energy studies of architectural projects [4]. The environmental tools include a wind tunnel simulator that allows users to visualize the air flow around digital 3D models. It simulates only major qualitative wind trends, and is intended to provide insight into wind patterns at early stages of building massing. Although the speed with which results can be obtained is useful during early project stages, the designer should be aware that the CFD analysis is not always especially accurate. However, this does not negate the usefulness of these results to depict general wind trends. Vasari can run files from Rhinoceros and Revit, and also includes a 3D-modeling function within the program [4]. In this design method, Vasari's horizontal data slices depicting wind speed (Figure 1) are used to evaluate the surrounding wind conditions that are created by each building form iteration.

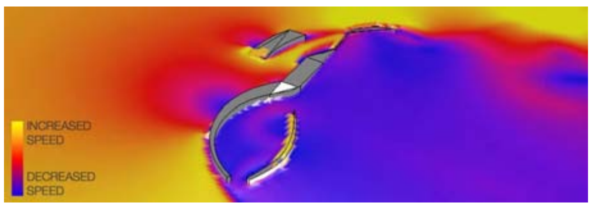

Figure 1. Horizontal data slice from Vasari, depicting wind speed at 2m above the ground.

2.4 Autodesk Flow Design

Autodesk Flow Design simulates a wind tunnel to allow users to visualize the air flow around digital 3D models [5]. The simplicity of the program's set-up and operation makes it ideal for designers who don't have the time or the need to learn a comprehensive CFD program. It simulates only major qualitative wind trends, and is intended to provide insight into wind patterns at early stages of building massing. Although the speed with which results can be obtained is useful during early project stages, but the designer should be aware that the CFD analysis is not always accurate. The program, however, is still useful in depicting general wind trends. Flow Design can run files from Rhinoceros, or can be used as a plug-in for Revit [5]. While Flow Design's horizontal data slices are not as detailed as those from Vasari, its vertical data slices depicting wind speed (Figure 2), flow line animations (Figure 3), and colour gradients representing the wind pressure acting on the model surface (Figure 4) are used in this method to visualize wind speed, turbulence, and pressure on and around the building.

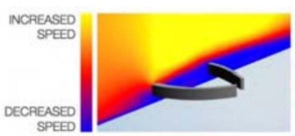

Figure 2. Vertical data slice depicting wind speed from Flow Design.

Figure 3. Flow line animation from Flow Design.

Figure 4. Colour gradient representing wind pressure on model surface from Flow Design.

2.5 Scan&Solve

Scan&Solve is a plug-in for Rhinoceros that allows the designer to apply materials, restraints, and loads to the Rhinoceros model, and then evaluates the model's reaction to the simulated forces [6]. The program works with native Rhinoceros geometry, and unlike many other FEA programs, it does not require a separate meshed model in order to perform the analysis [6]. The analysis can be quite accurate, depending on the grid resolution that is set by the user [7]. Colour gradients representing the displacement of the model under load (Figure 5), as well as deflection animations of the model under load (Figure 6), are the most useful output for this design method.

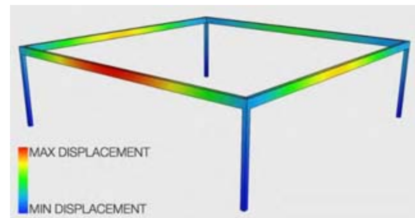

Figure 5. Colour gradient representing displacement from Scan&Solve.

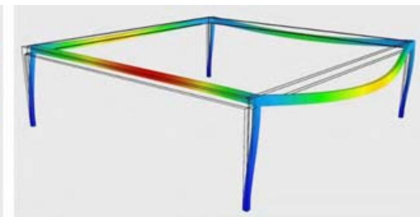

Figure 6. Deflection animation from Scan&Solve.

3 DESIGN METHOD CONDITIONS

For this paper, the design of a small, low-rise building is used as a means of developing the proposed design method that may be applied to many projects with varying building, program and site requirements. The paper does not serve to propose a specific building. However, to define the conditions within which this method is developed, a program and site have been chosen.

3.1 Program

The exterior program activities serve to provide a variety of wind condition requirements to be created with the building form, and are not a program proposal in themselves. These programs consist of pairings of wind energy generation technologies and seasonal sports that require specific wind conditions (Figure 7). To support the exterior programs, the building itself could accommodate energy storage, space to record and compare energy generation data from the wind energy generation technologies to be tested on the site, as well as equipment storage and change room facilities to support the sports programs. The building form does not reflect interior building design, program sizes or program placement requirements, but is instead a form that creates the wind conditions that are required for the exterior programs.

Figure 7. Wind conditions for exterior programs.

A set of drawings has been made that conveys the wind and spatial requirements for each exterior program, such as snowkiting, in which someone on skis or a snowboard is pulled across the snow by a large kite (Figure 8). These drawings may be referred to by the architect when developing building forms to create these required exterior spaces and wind conditions.

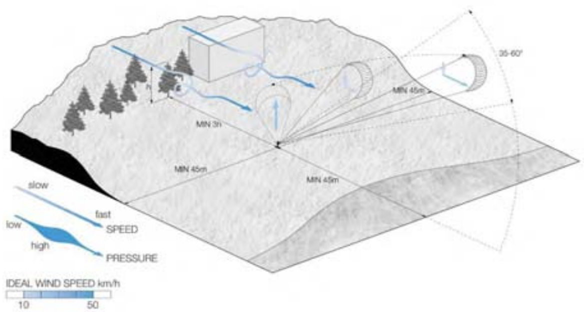

Figure 8. Wind and spatial requirements for snowkiting.

3.2 Site

The site on which the method will be developed is an open field on the outskirts of southern Regina, in Saskatchewan, Canada. Regina is one of the windiest cities in Canada, with an average annual wind speed of 20 km/h [8]. These high wind loads provide an extreme context within which to develop the design method, and the flat, open site provides an opportunity to manipulate the wind with only the building form, as there are minimal site conditions to alter the wind immediately around the building. The wind on the site comes predominantly from the south-east, but can also come from the north-west (Figure 9) [8]. The site is located near the University of Regina, whose existing wind turbine studies [9] could potentially pair with the wind energy generation technologies that surround the building.

Figure 9. Annual wind rose for site in Regina.

4 CFD PROCESS

4.1 Process Overview

For each building design iteration, CFD software is first used to simulate the speeds and patterns of wind flow around the building form. This tests the appropriateness of the surrounding wind conditions that have been created by the building form for the exterior programs that must be accommodated. The speed with which these results are provided allows the architect to refine and re-test many iterations of the design until the building form creates the desired wind conditions. The CFD software also evaluates the aerodynamics of the building form, as the software provides the architect with information about the wind pressure that is exerted on each building face.

4.2 Wind Effects Library

Manipulations of building form to increase and decrease wind speed, turbulence, and pressure were studied from a broad range of published sources [10, 11, 12, 13, 14] and compiled by the first author into a library of wind effects. For each technique, a wind effect that has been studied in real wind environments is compared with the results of the simulation of the effect in both Vasari and Flow Design, such as the drawing and simulations of the Venturi effect (Figure 10) [10]. While the wind effects library is too extensive to include in this paper, it is a part of the first author's Master of Architecture thesis. Architects may refer to this library of effects to alter the building geometry in order to create the specific wind conditions that are required for the exterior programs. The software simulations of each of the effects allow the architect to become familiar with what each of the CFD programs can accurately represent, and what they don't consider when computing results. For example, neither Vasari nor Flow Design is able to depict the downwash effect, as the programs assume a uniform wind speed and do not consider the higher wind speeds that exist in reality at higher elevations. It was also learned through these simulations that Vasari's horizontal data slices are more detailed than those from Flow Design, but Flow Design's vertical data slices, flow line animations, and colour gradients representing the wind pressure acting over the model surface are more accurate than those from Vasari. While CFD software can be a useful tool for quick tests of design iterations, the architect has to know how to interpret the results and be able to tell if they are an accurate representation of the simulated effects, by possessing some knowledge of studied wind effects.

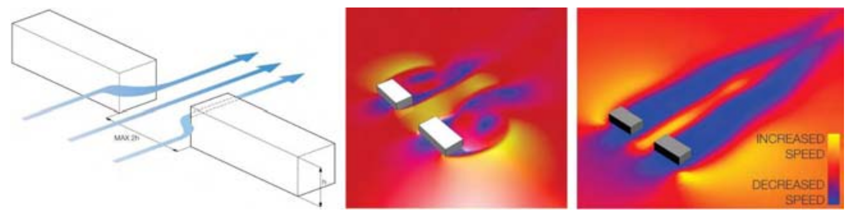

Figure 10. Studied effect, Vasari simulation, and Flow Design simulation of the Venturi effect.

4.3 CFD Process

For the first step in the process, a building form is modeled and tested with CFD software to visualize the wind speeds and patterns that are created around the building by the building form, and evaluate the appropriateness of these wind conditions for the exterior programs that are intended to be accommodated. This can be represented by Vasari's horizontal data slices of wind speed that depict general wind patterns. After the first building iteration is tested with the CFD software, the architect makes observations and adjusts the form for the next iteration to improve the appropriateness of the surrounding wind conditions for the exterior programs. These adjustments to the form may be made by referring to the wind effects library that was mentioned in section 4.2, which catalogues ways of manipulating form to increase or decrease the surrounding wind speed and turbulence. Iterations may also be tested in Flow Design to look at the flow lines, which depict the wind turbulence that is generated by the building. Although this adds an extra step to the process, it is beneficial to ensure that there is no undesired turbulence created by the building form. As CFD programs are improved in the future, the accuracy of this process will increase.

During these iterations, the CFD software is also used to evaluate the aerodynamics of the building form by depicting how much wind pressure is exerted over the model's surface. The amount of wind pressure that acts across the surface is represented by colour gradients in Flow Design. After each iteration is tested within the simulated wind conditions, the designer makes observations and adjusts the form for the next iteration to improve the form's aerodynamics. These adjustments to the form may be designed by referring to the wind effects library that was mentioned in section 4.2 and included in the first author's Master of Architecture thesis. These observations and adjustments are done concurrently with the adjustments to improve the surrounding wind conditions for the exterior programs.

To test this method, a building form was developed through nine iterations, improving the surrounding wind conditions or aerodynamics of the form with each iteration (Figure 11). The first few iterations were used to increase the width and length of the channel of increased wind speed between two buildings, and a later iteration refined the building geometry so that the required wind conditions would be created when the wind blew from either of the two predominant wind directions. The ninth iteration accommodates all of the exterior programs in a wide variety of wind conditions (Figures 12, 13, 14). After this iteration, the CFD process was stopped and the resulting building form was then used to develop the FEA process.

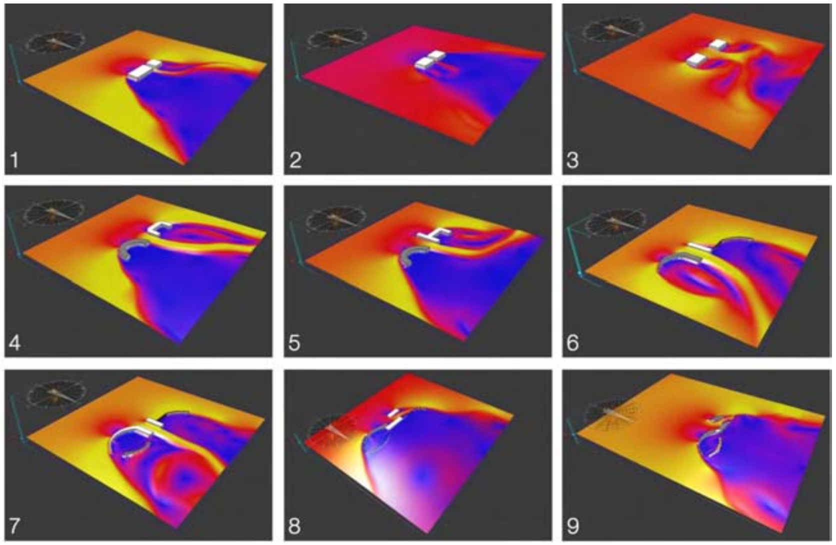

Figure 11. Iterations to improve wind conditions and aerodynamics of form.

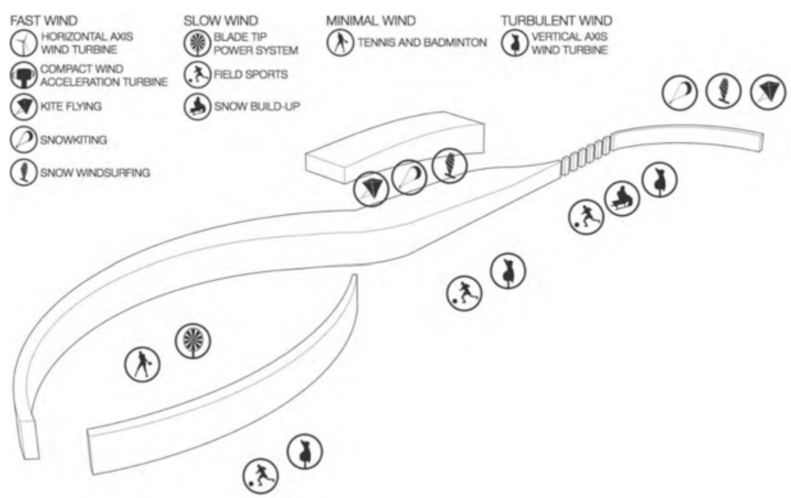

Figure 12. Ninth iteration with surrounding exterior programs.

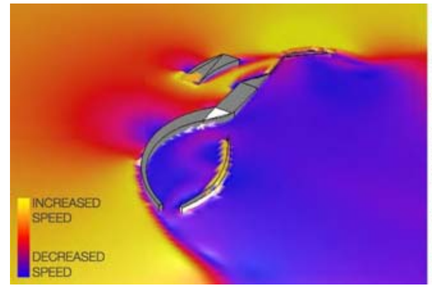

Figure 13. Wind speed data slice of ninth iteration at 2m above the ground.

Figure 14. Wind flow lines around ninth iteration at 2m above the ground.

5 FEA PROCESS

5.1 Process Overview

There are many structural systems that can be used to resist wind loads [15]. However, for the purposes of this paper, a steel-frame system has been chosen and the FEA process has been developed specifically for the planning of this type of structural system. The simplicity of the system provides an appropriate base with which to develop a methodology that could potentially be used for other structural systems. The modular nature of the system also allows the architect to design small units of structure that are repeated throughout the building. This creation of a single unit may be applied to buildings of various sizes, as the units may be repeated throughout the building as many times as necessary.

The FEA process is used to develop a digital model of a single structural bay. The wind pressure that is provided by the CFD software, combined with gravity loading, is input into the FEA software to predict how the bay will respond to this combined loading. Based on the deflection animation and the colour gradient that represents the displacement of each point of the model, the architect can see where and how much the bay will deflect in the wind and under gravity. The architect can then stiffen the bay against this deflection, and run the finite element analysis on multiple iterations of bays, with the goal of increasing the stiffness of the assembly each time.

5.2 Pressure Zones

The first step in the FEA process is to divide the building mass that has been created in the CFD process into different pressure zones, based on the colour gradients representing wind pressure on the model's surface that are obtained from the CFD software (Figures 15, 16).

Figure 15. Colour gradient representing wind pressure on the model's windward surface.

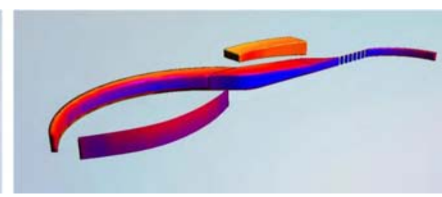

Figure 16. Colour gradient representing wind pressure on model's leeward surface.

The building is divided into six pressure zones (Figure 17) based on the areas that are subject to the same amount of wind pressure, as depicted by the colour gradients from the CFD software (Figures 15, 16). Then, the average positive and negative wind pressure values for each zone are obtained from the CFD software for each of the site's two predominant wind directions. For the purposes of this method, each zone is assumed to be subjected to the highest combined wind pressure and suction, out of the values obtained from both wind directions. These values are shown in the pressure zone matrix (Figure 18), although their accuracy depends on the level of accuracy that may currently be obtained from the CFD software.

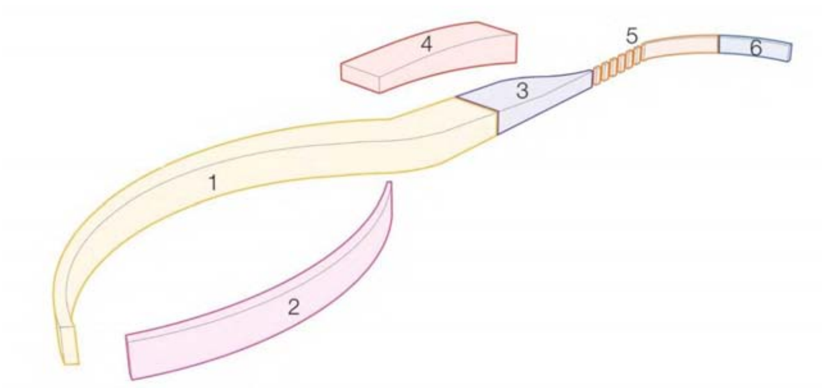

Figure 17. Building divided into six pressure zones.

	ZONE 1	ZONE 2	ZONE 3	ZONE 4	ZONE 5	ZONE 6
POSITIVE PRESSURE	8 Pa	1 Pa	1 Pa	8 Pa	4 Pa	4 Pa
NEGATIVE PRESSURE	-18 Pa	-10 Pa	-22 Pa	-3 Pa	-22 Pa	-18 Pa

Figure 18. Pressure zone matrix with highest pressure and suction for each zone.

5.3 FEA of Building Massing

The wind pressures and gravity loading are then input into the FEA software and applied to the massing model of each pressure zone, as shown for zone 1 (Figure 19). The colour gradient that represents the displacement of each point of the model, as well as the deflection animation (Figure 20), reveal areas within the zone that may deflect more while under wind load than other areas within the zone. In the case of zone 1, the form deflects the most at the right side, where the massing is the thinnest (Figure 20). As such, zone 1 has been divided into two sub-zones: 1A and 1B (Figure 21). These sub-zones are subjected to the same amount of wind pressure, but require different structural configurations due to the difference in geometry thickness.

Figure 19. Wind pressures and gravity loading applied to massing of pressure zone 1.

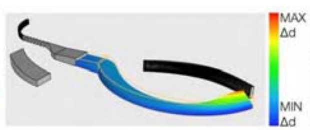

Figure 20. Deflection animation of pressure zone 1.

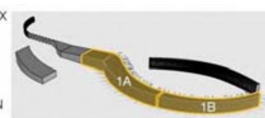

Figure 21. Zone 1 sub-zones.

5.4 Structural Bays

A structural bay is then modeled for zone 1A, and tested with the FEA software by inputting gravity loading and the wind pressure for zone 1. The deflection of the bay in the wind is observed with the displacement colour gradient and deflection animation, and if there is too much deflection, the architect adjusts the model of the bay to increase its stiffness and reduce its

deflection under wind loading. This may be accomplished by reducing column spacing, increasing member sizes, or adding bracing. This process is repeated until a bay is developed that has appropriate column spacing, member sizes, and bracing to resist large movements in the wind. Four iterations are shown to develop a structural bay for zone 1A (Figure 22), and the process is repeated for zone 1B, as well as zones 2 through 6 to develop a structural bay for each pressure zone within the zone's specified wind pressure conditions. Reducing the scope of the structural design to a single structural bay allows the architect to avoid the time-consuming task of modeling and testing the entire building's structure, while still being able to understand the column spacing, member sizes, and bracing that will be required throughout the building.

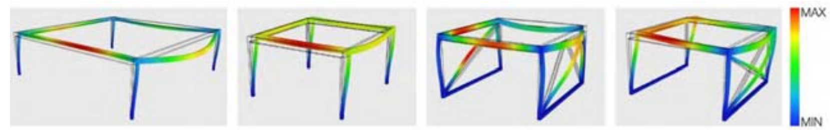

Figure 22. Iterations to develop a structural bay for zone 1A, showing amount of displacement of each point under load.

This method does not intend for the architect to replace the structural engineer. In a later design phase, the structural engineer would perform a more thorough structural design and analysis and would likely make adjustments to the structural bay that is developed with this method. The importance of this method is that it provides the architect with a sense of the approximate structural spacing, as well as an understanding that some form of bracing will be required. The architect can account for this while designing the building interior, so that no design decisions compromise the approximate structure that must be accommodated. This method provides a way of integrating structural considerations into the initial building design, which improves collaboration between the architect and the structural engineer throughout many design phases.

5.5 Structural System

After a structural bay has been developed for each zone and sub-zone, the bays are inserted within the massing to create the building's structural system. This schematic structural drawing (Figure 23) provides the architect with a comprehensive visual of the required structural density throughout the building. The architect can use this visual to design the building’s interior and the exterior facade. If larger member spacing would be beneficial in certain areas to create larger open spaces, the architect can test new bays with the FEA software, using the same iterative process to increase the column spacing, while also increasing member sizing or adding bracing to compensate for the longer spans. Once such a bay has been developed so that its deflection in the wind is acceptably low, these larger bays can be inserted where they are needed within the building. The architect can repeat this process as necessary until the structural and architectural designs work together, and neither compromises the other.

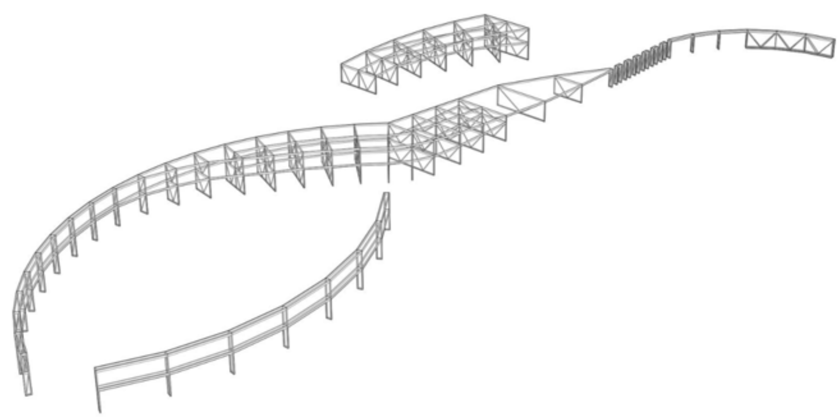

Figure 23. Drawing of the building's structural system.

5.6 CFD Analysis of Modified Form

The form of the building can then be adjusted to reflect the inclusion of the steel structure (Figure 24). For example, curved sections could be faceted, with each side length equal to the length of the column spacing. This modified form is then re-tested with the CFD software to ensure that the change to the form did not undesirably alter the wind conditions around the building (Figure 25). If the wind conditions are found to have changed in certain areas, this would affect the wind pressure that is applied to that area of the building. A new pressure zone would be created and a new structural bay for that zone would be developed with the same iterative FEA process. If the wind conditions are altered so much as to become undesirable, the form itself would need to be adjusted so that it fosters the intended wind conditions, yet is also an appropriate shape to be able to accommodate a steel-frame structure. This step completes the feedback loop between the CFD and FEA programs, and at this point, the design method may be repeated as many times as necessary to develop a building that both shapes and resists the wind.

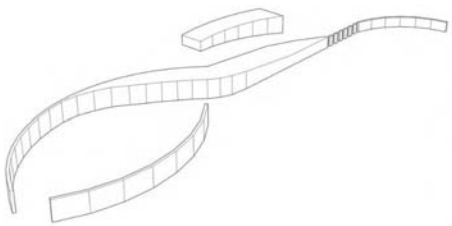

Figure 24. Adjusted building form to reflect the inclusion of a steel structure.

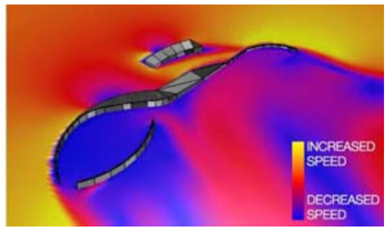

Figure 25. CFD software test of adjusted form.

6 CONCLUSION

A design method in which architects use wind effects and loading as a design generator may be carried out with a pairing of computational fluid dynamics software and finite element analysis software. Using CFD and FEA software in a way that is appropriate for architectural applications allows architects to integrate wind and structural engineering considerations into the early design stages of their current working practices. As CFD and FEA programs continue to be improved, the accuracy and usefulness of this method will increase. It is the hope of the authors that software programmers may draw from this method to create CFD and FEA programs that are conducive to architectural applications, so that in the near future, architects may use this design methodology to integrate wind, structural and architectural design processes.

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